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THE VEINS OF COBALT, ONTARIO.

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INTRODUCTION.

Silver veins containing cobalt and nickel, though rare, have long been known. The deposits of Annaberg, Saxony, were discovered as early as 1492, and those of Joachimsthal, Bohemia and Chalanches, France, in the late part of the eighteenth century. The discovery of the ores at Cobalt was made in 1903 and in a few years the mines of this district became greatly productive.

In 1911, the maximum of production, 31,500,000 ounces of silver, was reached. In 1917, the production of 19,401,893 ounces gave a total of 274,725,000 ounces. The total production to date may be estimated as 315 to 320 million ounces with a value of about $200,000,000. The returns from the older deposits, now almost unworked, have been far surpassed, probably more than doubled, by the output of the Cobalt district.

The peculiarity and richness of the vein-type has drawn much attention from geologists. Excellent descriptions[1] of the European deposits are available and, among the many publications concerning Cobalt, those of Miller[2] discussing also the deposits at Gowganda and South Lorrain are preëminent. Many points have, however, remained obscure and, as data of interest have been obtained during a year's examination[3] of all the important mines of the district, the present contribution is offered.

GENERAL GEOLOGY.

Basement Complex.

The most ancient rocks of the district are Keewatin schists and greenstones of volcanic and intrusive origin, and dark slates correlated with the Grenville series. Intrusions of Laurentian granite, now largely gneiss, have penetrated these rocks. This complex is exposed in the mines and is considered in this paper a unit, called, as is the custom at Cobalt, the "Keewatin."

[1] *Annaberg Saxony.* H. Müller, "Die Erzgänge des Annaberger Bergrevieres," Geol. Landesanstalt Leipzig, 1894.

Schneeberg, Saxony. K. Dalmer, E. Köhler and H. Müller, "Section Schneeberg," *Geol. Spez. Karte Sachsen,* 1883.

Joachimsthal, Bohemia. J. Step and F. Becke, *K. Akad. Wis. Wien Sitzungsber,* vol. 113, 1904, pp. 585–618.

E. S. Bastin and J. M. Hill, Prof. Paper 94, U. S. Geol. Survey, 1917, p. 122.

Chalanches, France. T. A. Rickard, *Trans. Am. Inst. Min. Eng.,* vol. 24.

[2] W. G. Miller, "Cobalt-nickel Arsenides and Silver Deposits of Temiskaming," Fourteenth Ann. Rept., Ont. Bur. Mines, pt. 2, 1905; *idem,* Sixteenth Ann. Rept., pt. 2, 1907; Nineteenth Ann. Rept., pt. 2, 1913.

[3] The investigation of the geology of Cobalt was made in 1916 by Alfred R. Whitman for the mining companies of the district. The author, his assistant, wishes to acknowledge that many data and most of the structural conclusions of the paper are due to Mr. Whitman.

Huronian.

The Temiskaming.—The sediments correlated somewhat doubtfully with the Huronian are the Temiskaming and Cobalt series. The Temiskaming conglomerate, of slight importance in the economic geology, is well bedded and lies in a vertical or almost vertical attitude. It is cut by lamprophyre dikes which do not penetrate the younger strata, and by the Lorrain granite, pebbles of which are found in the Cobalt conglomerate. The latter is separated from the Temiskaming by a marked unconformity.

The Unconformity.—The plane of this unconformity was studied in great detail. Contour maps and models of its surface were made where sufficient data were available. Conclusions differ from Miller's[4] statement that "the surface . . . was uneven and possessed . . . higher hills and deeper valleys than those of the present surface." The surface of erosion on the Keewatin and Temiskaming was found to be remarkably smooth and flat, and its original irregularities were much smaller than the topographic features of the present surface. Several minor hills and valleys on the old surface were mapped; but the major undulations are due to folding.

The Cobalt Series.—The basal coarse conglomerate and breccia of the Cobalt series is overlain by several beds of fine-grained, delicately bedded, slate-like graywacke alternating with conglomerate layers of varying thickness and fineness. The graywacke is in lenticular, limited beds, feathering out at the edges or grading into coarser material. Over it lies a second massive conglomerate.

The Cobalt series is believed to be of normal stream origin. Striated pebbles, which have been mentioned[5] as an indication of the glacial origin of these strata, were found during the investigation, but are believed crushed by the dynamic deformation of the rocks. The parts of the basal conglomerate resembling residual soil and breccia, the well sorted character of many beds and the usual stratification unite to offer proof of fluviatile origin.

[4] W. G. Miller, Nineteenth Ann. Rept., Ont. Bur. Mines, pt. 2, 1913, p. 76.

[5] A. P. Coleman, *Am. Jour. Sci.*, 4th ser., vol. 23, 1907, pp. 187–192; *Jour. Geology*, vol. 16, 1908, pp. 149–158.

Nipissing Diabase.

Intrusion of the diabase is believed to have been of Keweenawan age. It cuts the older rocks in a plunging and arching sill of 1,100 feet approximate thickness. Within the Cobalt area the sill was injected chiefly in the Cobalt series, and at an angle of 40°, cross cuts at a maximum beds dipping 10° near Kerr Lake. The plunge of the sill between Kerr and Peterson Lakes (Fig. 15) lifted a block of the Keewatin about 1,000 feet. Three remnants of this block have been preserved during erosion. In the southeastern part of the district, projections of the sill penetrate the Keewatin of the roof for short distances and blocks of Keewatin are found imbedded in the diabase. At South Lorrain the sill is in the form of an arching dome truncated by erosion. In the Gowganda area the diabase is in places dikelike and irregular. The varied forms are believed an indication of many offshoots from a deep-seated mother magma, attempting to rise through devious channels and spreading out beneath a barrier. Sporadic masses of pegmatitic material indicate merely incipient differentiation.

Post-Nipissing Dikes.

Dikes of aplite or granophyre cut the Nipissing diabase at Cobalt (Fig. 15), Gowganda and Elk Lake. Both chemically and microscopically these rocks appear to be genetically related to the diabase.[6]

A basalt-diabase dike intersects the Nipissing sill at Cross Lake, Cobalt.

Silurian-Recent.

Limestone outcrops north of the district are of Silurian age. Since the Silurian, erosion has been predominant and a great thickness of rock has probably been removed.[7] The ice sheet of the Pleistocene has carried away detritus and has left the exposed rocks but slightly weathered.

[6] W. G. Miller, *op. cit.*, p. 104.
[7] W. G. Miller, *op. cit.*, p. 114.

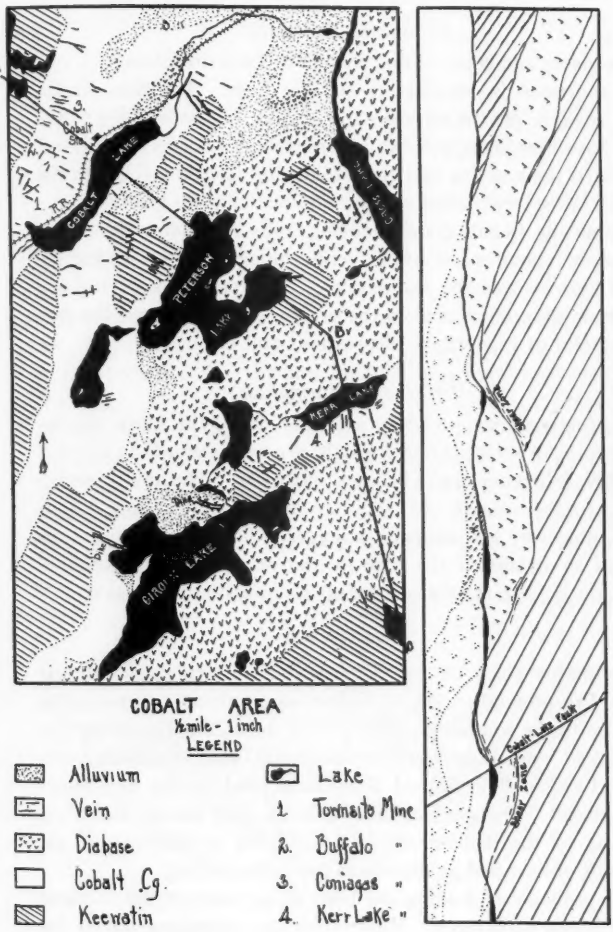


FIG. 15. Geologic map and ideal section of Cobalt area.

STRUCTURAL GEOLOGY.

Significant Drainage.

The rivers and lakes of this portion of Ontario follow two systems expressed in intersecting straight lines. The first, northwest, is more prominent than the second, northeast (Fig. 15). They have been interpreted to be of structural origin and Miller[8] correlated the syncline and fault following Cobalt Lake with the N.E.–S.W. system of the region.

Within the Cobalt district, folds, faults and joints have been formed by compressive forces acting along the lines of the regional systems and the magnitude of the force appears to have been roughly proportional to the present prominence of the parallel system of topographic depressions and drainage.

Period of Deformation.

The forces of compression, which produced the folds, are believed to have acted during a single period, indefinite in age but probably following the Nipissing intrusion. The major structures are thus nearly of simultaneous origin. Many minor joints, however, are distinctly younger. Their formation is attributed to strains of the rock by the residuals of the original forces during the release of vertical compression by erosion.

Folds.

The major folds of the district follow northeast-southwest axes. Prospect hill, west of Cobalt, approximates a monocline with dip to the southeast. The axis of a syncline lies along Cobalt Lake. Anticlines occur at Cobalt hill, east of Cobalt Lake, at the Lawson hill, east of Kerr Lake, and at the McKinley-Darragh hill. The synclinal axes coincide with basins due to the plunging of the diabase sill. The original undulations of the Nipissing sheet acted as determinants to the folding.

Less pronounced folding has been along axes normal to those of the major structures. Minor folds are superimposed on the greater and lie usually upon the limbs of an anticline or syncline with the axes pitching with the dip of the latter.

[8] W. G. Miller, *op. cit.*, pp. 116–119.

The folds have gentle slopes. Dips of 10–20 degrees are common and that of 35 degrees is a maximum.

Fractures.

Faults.—The faults of the area are all reverse faults. The familiar dip-slip fault is the usual form, but displacement is often principally lateral.

The great fault of the district, the Cobalt Lake fault, is a dip-slip fault dipping 50–60° and of 400–500 feet displacement (Fig. 15). It is parallel to the N.E.–S.W. structural axis. In one notable case its plane is warped by a minor fold. Other major faults parallel to this line or its normal complement have not been found.

The common, flat, dip-slip fault is, in origin, connected with the folds. It is well known that shearing stresses are developed parallel to a surface of folding, and that the strains resultant from these stresses are concentrated in zones of weakness. In the Cobalt area the relief of these stresses took place on or near the contacts, particularly the contact of the Cobalt series with the Keewatin. In these zones, dip-slip faults, 10–30° in dip, are numerous.

The strike-slip faults, of east–west strike and dip varying from 50–75° (Fig. 16), are more difficult of explanation. The

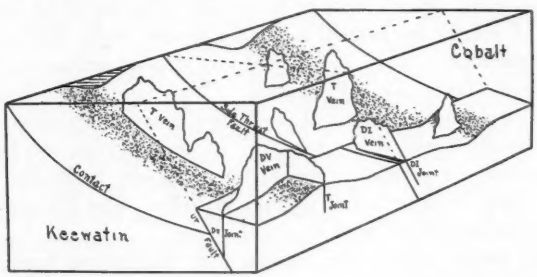


FIG. 16. Stereogram showing ideal structures and veins on limb of a major syncline.

two normal horizontal systems of compression, however, would give rise to a great ellipse of strain in the rock mass of the district. Planes of no distortion would have an approximate east-west strike and horizontal shearing would take place parallel to these planes.[9] The strike-slip faults appear to be the expression of this resultant of the stress systems.

Joints.—The major joints of economic importance are due to dynamic deformation. Their connection with structural features has proven of great practical value in permitting the prediction of new veins. Several of the types have hitherto remained undescribed; but are believed to be not necessarily unique to the Cobalt area. Such joints are relatively few in number, are not of striking appearance except where mineralized and may prove to be of widespread occurrence.

Certain joints are in definite relation to minor folds. The more common (T joints) are vertical, discontinuous or often gash-like along the strike, but extend in a connected series in planes of great vertical and horizontal dimensions. Upon a minor anticline on the limb of a major syncline, they lie parallel to the axis of the anticline (Fig. 16). Upon a minor syncline similarly placed, they lie normal to the axis of the minor structure. Another type (T_1 joints) are vertical, of smaller area and strike parallel to the dip of the minor folds. These joints (T and T_1) are inferred to be due to local tensional stresses.

Many joints branch from or lie parallel to the planes of faults; some (S joints) are parallel to the flat reverse faults of the contact shear zones. They were formed by stresses similar to those causing the faults; *i.e.*, by shearing. Other joints (DV joints), similar in character to those of the T class, diverge vertically from steep dip-slip faults (dip 50–65°). In another type, the joints (DI joints) lie parallel in dip to the strike-slip faults, but diverge from the latter a few degrees in strike. The DV and DI classes are believed to be of tensional origin.

Many minor joints were formed with the greater fractures. Typical systems of small joints are to be observed. Later joints,

[9] G. F. Becker, "Finite Homogeneous Strain, Flow and Rupture of Rocks," *Bull. Geol. Soc. Am.*, vol. 4, 1893, p. 23.

particularly in the diabase, intersect to form rhombohedral blocks.

Fracturing and Rock Character.—The Keewatin is a plastic formation. In it the joints are erratic. The stronger *T* joints, however, occur in expected positions. Faults flatten in dip and frequently change in strike upon entering the Keewatin. Here they have well defined, slicken sided walls, considerable gouge and are bordered by zones of brecciation or shattering. They show discontinuity and are often distributive on a number of offset planes arranged in echelon.

The Cobalt series across the beds is highly elastic; parallel to them it is easily sheared. Flat shearing stresses have thus found ready relief in this rock. The vertical joints, capable of formation in it, are persistent for hundreds of feet.

The diabase is the most homogeneous rock, and is elastic and tough. The joints frequently exhibit conchoidal curvature, and faults may have sinuous courses. The stronger vertical joints are persistent.

THE VEINS.

General Character.

In the typical veins of the Cobalt district sulphides, sulpharsenides and arsenides of nickel and cobalt occur with native silver in a gangue of calcite and dolomite; more rarely these minerals are accompanied by native bismuth, dyscrasite, breithauptite (NiSb), argentite, ruby silver, lead, zinc and iron sulphides and silver amalgam. The outcrops in many places show the brilliant purple-red and the soft apple-green colors of erythrite ($Co_3As_2O_8 + 8H_2O$) and annabergite ($Ni_3As_2O_8 + 8H_2O$). The veins are characteristically narrow, ranging in width from an inch or less to a rare maximum of perhaps four feet. The stopes are thus usually narrow, but where country rock of slaty character has been impregnated with ore on the joints, a width of forty feet has been attained. Such "wall rock" is rendered payable as a low grade ore by minute plates of native silver, of dyscrasite, of ruby silver, and more rarely of argentite deposited in the cracks and joints. Values in the veins are almost entirely due to the silver content, for cobalt until recently has been recov-

ered from the ore only in small quantities. Silver assays are often high (7,000–10,000 ounces per ton) and are commonly encountered well above 1,000 ounces per ton. Indeed ore below the tenor of 800–1,000 ounces of silver per ton has in the past been characterized by the miners as "low grade." The attitude of veins in the district is varied; but the generalization is well proven that flat dipping veins are barren or nearly barren of silver. The economically important veins are of steep dip or are vertical.

Types of Veins.

The veins usually exhibit characteristics typical of the dynamic origin of the vein fissures. Mineralogically, therefore, the veins may be considered as (1) flat or shear (*S*) joint veins; (2) fault veins; (3) inclined joint veins; and (4) vertical joint veins.

Shear Joint Veins.—The gently dipping shear (*S*) joint veins are composed chiefly of calcite of pink color. Gouge occasionally occurs as a thin clay seam at one contact of the vein. The calcite of the vein is often spotted with irregular areas of white quartz, which in some of the flatter veins attains marked development. Galena, chalcopyrite, and sphalerite occur usually irregularly intergrown in massive, coarsely crystalline lenses in the calcite. Pyrite is often to be observed associated with these sulphides, and also in concentrically crustified spherules. Banding of disseminated sulphides, of arsenides, and of residuals of the wall rock, with vein calcite is sometimes present. When such veins cut Keewatin basic rocks, or diabase, needles of tremolite often penetrate the typical calcite. These veins are essentially barren. Scales of native silver, proustite, dyscrasite and argentite lie upon small flat joints, and rich irregular masses of proustite, native silver, and amalgam rarely are to be found in calcite containing some arsenide. Such deposition of silver is always of local occurrence upon shear joint veins, and is confined to the immediate vicinity of rich vertical veins or of faults.

Fault Veins.—Fault veins are mineralized in a manner distinctive and peculiar to this type in the Cobalt area. The calcite, which is the chief constituent of these veins, varies in color from

white and pale pink to red. It is often banded with a green chloritic material, probably representing an altered phase of crushed rock, and where in contact with the heavy gouge of the faults, it penetrates the soft clay in imbricating veinlets. Chalcopyrite, galena, zincblende, and rarely argentite or proustite, occur as nodules in the crushed walls. Bismuth lies in minor veins parallel to a main vein and is associated also in irregular masses with the arsenides of the chief veins. The arsenides, niccolite and smaltite, are in places massive, but more commonly occur as crushed nodules in heavy calcite veins. Pyrite and sphalerite occur in fractures in the calcite and are apparently later in deposition than the arsenides. Ruby silver is found on such fractures associated with pyrite and its accompaniment of white calcite of a second deposition. Native silver penetrates the massive and nodular arsenides, lies in fractures in the calcite and often occupies cavities in the form of "wire silver." The native silver, in spite of the common occurrence of sulphides and sulpharsenides of silver, in the fault veins, is the source of most of the silver content.

Inclined Joint Veins.—The steeply dipping veins upon *DI* joints show characteristics similar to those of the fault veins. They have been in places of great width and richness as in the 64 vein of the Nipissing.

Vertical Joint Veins.—The vertical joint veins (Plate VII., *a*, *b*) are often apparently massive aggregates of the arsenides, smaltite, niccolite, chloanthite and maucherite; of the antimonides, dyscrasite and breithauptite; and of native silver. Niccolite, smaltite and native silver predominate. Upon careful examination, however, the massive structure is seen to be an intergrowth of these minerals with white calcite, subordinate in amount. Arborescent and concentric or spherulitic arsenides and antimonides are imbedded in a matrix of calcite. A characteristic arrangement is that the spheres of arsenide have a central nucleus of niccolite or copper-colored arsenide and that the outer layers of the concentric structure contain the silver gray cobalt minerals. These spheres range in diameter from 1 to 20 millimeters; but are usually about 5 millimeters across. Silver occurs in the spherules

and in the calcite in wandering irregular veinlets, often locally following cleavage, and in arborescent forms much like those at times seen of the arsenides. Changes in the proportions of these constituents are often quite sudden in the vein. Smaltite spherules with niccolite cores, within a few feet vertically, have been observed to give place to pure niccolite or to pure smaltite. Ore of ordinary grade containing arsenides, particularly when high in niccolite, often passes within a few feet into ore of extremely high grade composed of silver and calcite alone. Such phenomena are to be seen usually at the end of a branching, gash-like component of a vein, or at cross fissures.

Less common structures are banding, crustification and certain phenomena involving fragments and alterations of wall rock. Banding involves niccolite, smaltite, white and pink calcite, and rarely pyrite. Veins are banded often with pink calcite at the contacts, and with white calcite at the center. This white calcite contains, in the characteristic patterns, niccolite, smaltite, and silver. Banding is seldom symmetrical, and often one contact of the vein is found to be composed of a hard black gouge resembling graphite. The banding in such a case has been observed in the series; gouge, white calcite (thin), breithauptite and niccolite, niccolite high in silver and coarse pink calcite. Many veins are irregularly banded with white calcite at the center and smaltite at the contacts. Such a phenomenon has been observed from the small scale of veinlets a fraction of an inch across to the extraordinary development of a vein a foot in thickness composed of a center of clean white calcite and of a massive band of smaltite three to four inches thick at each contact. Crustification is not postulated for the prevalent banding but has been found in the deposition of calcite upon a certain open fissure.

Fragments, however, are common in the veins (Plate VII., *a*). They vary in size from small pieces of chloritized rock surrounded by arsenides to large angular and unsupported blocks suspended in the vein filling. Bedding, which may give an indication of the relation of attitude of adjacent fragments, is seldom to be seen; but of veins portraying this feature, in some, the frag-

ments seem undisturbed and the bedding of all to be parallel (Plate VIII., *a*); in others, the fragments have certainly been crushed and rotated. The walls of certain veins have been altered by the deposition of many minute areas of calcite throughout the rock. The calcite of the vein is in sharp contact with this altered phase of the rock; but the latter fades gradually into the typical country rock of the district (Plate VIII., *b*).

DISTRIBUTION OF TYPES.

	Vertical Joint Veins.			Dipping Joint Fault.		
Structure	*T*	T_1	*D*	VI	*Fst*	*Fut*
Number	110	28	22	14	8	5
Per cent. of number	74%		12%	7%	7%	

[10] *Fst* indicates strike-slip faults. *Fut* indicates dip-slip faults.

Ore Shoots.

Inclined Veins.—Upon the greatest dip-slip fault of the area, the Cobalt Lake Fault, ore occurs in relation to folding, which has warped the fault plane. Upon the limb of a major syncline whose axis is parallel to this fault, minor folds lie with their axes at right angles to the fault and to the main synclinal axis. Opposite minor synclines the fault has been bent away from the axis of the major syncline; opposite anticlines it has been warped in the reverse direction. The ore occupies shoots along the dip of the fault plane opposite the anticlines. Faults and parallel joints (*DI*) elsewhere contain ore-shoots which appear definitely connected with gently dipping cross faults of the shear system. Above an intersecting fissure, which often contains calcite, the ore spreads out fan-shaped upon the fault or joint plane, and at its periphery passes laterally and upward into the barren calcite of the typical vein.

Vertical Veins.—The concentrations of ore upon the joint veins are invariably in definite relation to faults and shear zones (Fig. 19). Upon the *DV* joints, which branch vertically from reverse faults, the ore lies upon the joint near the fault. Fragments show at times rotation, and movement has probably taken

place upon these joints. Argentite occurs at the intersection of fault and vein in the McKinley-Darragh and LaRose mines, and in such a vein has been described to be due to supergene processes. The observations during the present investigation of the veins indicate that the rare occurrence of silver sulphides upon vertical veins in the Cobalt district is confined chiefly to veins upon the *DV* class of joints.

Veins striking perpendicular to steep faults have been enriched by ore near the intersection. In such veins silver-rich niccolite and breithauptite occur nearest the fault, lower grade smaltite with niccolite cores and more calcite farther away, and at the periphery of the shoot barren smaltite in narrow veins passes by transition into thin veins of pink calcite.

By far the greatest number of ore-shoots in the district are determined, however, by flat dipping shear zones or faults. Such faults lie in many places in a zone of movement upon and near the Huronian-Keewatin contact. Similar planes of movement, de-

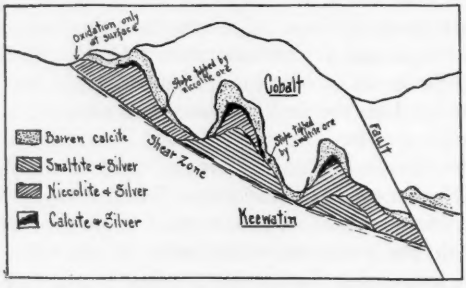
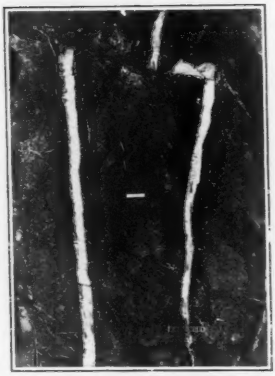


FIG. 17. Ideal section on plane of a vertical view. Bottom of vein approximately 500 feet below surface.

flected from this contact by irregularities, primary or due to folding or faulting, lie partly in the Huronian sediments or, where formed with no relation to the contact, lie wholly in these sediments. Other contacts as those of the diabase and Keewatin, and of the diabase and Huronian are loci of similar movement and such shear zones may lie also within the diabase. Where

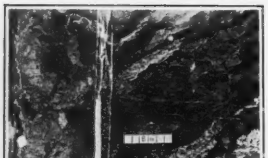
a.



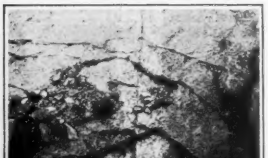
b.

c.

a. O'Brien Mine. Rich vein of smaltite (gray) and white calcite in diabase. Drift face.
b. Nipissing Mine. Typical nicolite veins. Drift face.
c. Townsite Mine. Vein showing contact relations of arsenide and slate. Cobalite crystals in slate.

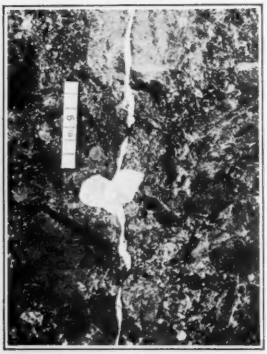


a.



b.

c.



d.

a. Vein subsequent to faulting of joint in slates. Note bedding of slates and fragments in vein. Stope face.

b. Lawson Mine. Vein on surface alters rock at contact and projects into a cross joint. Horizontal.

c. Nipissing Mine. Faulted niccolite vein with pebble projecting from wall. Drift face.

d. Coniagas Mine. Veinlet replacing pebble. Stope back.

faults are distributive on the bedding of slates great masses of low grade ore have been formed near veins. Above the contact or near a fault plane, which is usually heavily mineralized by calcite, fan-shaped ore-shoots lie in the vein and possess typical peripheral mineral variations. Nearest the fault the vein contains predominantly smaltite often with dull silver-gray cores of a mineral, probably cobaltite. Away from the ore-center, niccolite cores in smaltite spherules are encountered and transition takes place in turn between these spherules into massive niccolite. At the periphery sparsely disseminated niccolite or smaltite spherules pass into pure calcite of pinkish color. Silver content decreases gradually but surely from the central axis, near the fault, to the periphery of the shoot (Fig. 17).

Such ore-shoots have been developed in their lower portions 1,000 feet or more laterally, and have extended nearly 250–300 feet vertically. Many do not outcrop; indeed their upper portions are often 300 feet or more below the surface and smaltite with native silver has been found 1,600 feet in depth at the Beaver Mine.

Classification.

The relations of mineral content of the veins to their dip, and of ore-shoots to faults, have been encountered in the district so frequently that a simple and graphic classification is possible. In

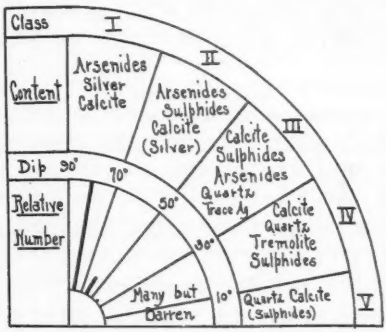


FIG. 18. Classification of veins by attitude and contents.

this classification the data of 187 stoped veins examined in the district are included. The contents, attitude, and type of ore-shoot of a vein are expressed in two simple symbols.

Any vein may be completely described and classified at *A*I, *D*I,

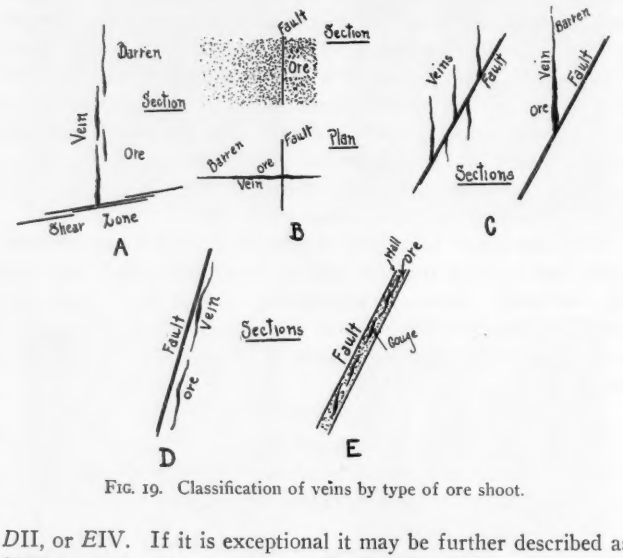


FIG. 19. Classification of veins by type of ore shoot.

*D*II, or *E*IV. If it is exceptional it may be further described as *E*IV (+Ag), *A*I (—Ag), or *A*I (+S). Such exceptions are rare.

VEINS CLASSIFIED.

	I.	II.	III.	IV.	V.
A.....	126	6			
B.....	17	1			
C.....	20	2			
D.....	10	6			
E.....	2	14	1	Many barren veins	Many barren veins

Age Relation of Veins.

The relationship of veins one to another and of veins to structures is both economically and scientifically of prime importance.

The fact that all the major fractures of the Cobalt district are mineralized seems at first to simplify the matter, but the possibility of faults displacing veins and later being cemented by calcite must be considered. The intersection of a vertical ore vein and a flat fault vein, however, shows almost invariably continuity between the two veins. The character of the filling changes, it is true, but the change takes place usually by transition. Arsenides occur locally upon the flatter, shear structure, in their characteristic form of spherulitic aggregates. Drag, crushing or other evidence of displacement of the vein after its formation is lacking at the contact of fault and vein. In places ore of the typical composition is to be found upon a fault plane and crushing and recementation has sometimes taken place, but that this ore has been derived from drag left by the faulting of a vertical vein of the characteristic arsenide type, is impossible. Near such ore-shoots upon faults, ore veins do not occur in intersection with that fault, the shapes of the ore-shoots are not in accord with the shape to be expected from drag, and excellent structural reasons are to be found for original deposition of ore in just such loci upon faults.

Parallel veins, however, are to be found in opposite walls of a fault and separated by an interval equal to the displacement upon the fault. These veins, at their intersections with the fault, show the phenomena of intersection just described. Their corresponding extremities usually do not match; that is, the mineralization is quite different in character in the two extremities. A vein of high grade smaltite ore may abut against a fault on the hanging wall while the corresponding vein in the foot wall perhaps removed 10–20 feet may be of low grade smaltite with niccolite cores, or of barren calcite. Such relations are a strong indication that the vein fractures have been faulted and that later mineralization has caused, according to local conditions, depositions of varying character in the faulted remnants (Fig. 17).

Small faults in places undoubtedly displace the veins; but they are of exceptional occurrence and are always of slight throw, a few inches to a rare four feet. Upon these faults, where flat, barren calcite has been deposited, and in several cases of very

steep faults (75°), a few inches of banded, perhaps crustified, galena, pyrite and sphalerite were noted. These minor veins are distinctly later than the main mineralization.

It may be confidently stated that in the Cobalt district, vein fissures have been faulted, but that the veins have not been materially displaced. Slight movements, expressed by reverse faults with weak veins, and subsequent to ore formation, give excellent indication that, after a single period of mineralization, while the rocks were still subject to lateral compressive forces, these forces in expiring gave rise to feeble dynamic manifestations later than the veins.

PROCESSES OF VEIN FORMATION.

Open Filling.

Evidence of open filling is confined to two classes of veins. Upon the vertical fissures in the hanging wall of a reverse fault, movement no doubt took place. Fragments were broken and rotated, and as no great pressure was acting upon these joints the fragments tended to keep the walls of the fracture separated. Mineralization ensued and the vein was formed at least in part by open filling. Crustification of calcite in a cavity and rotation of bedded fragments in a vein offer corroboration of open filling in *DV* joints. Upon the joints parallel to strike-slip faults (*DI*) similar conditions resulted from the movement of the faults to which these joints are related. Open filling, as proved by crystalline crustification, took part in the formation of certain veins in such structures.

Replacement.

The veins of the faults and shear joints, which are thought to have been kept closed during ore-formation by the lateral compressive forces which produced them, show no crustification. The shear joint veins often enclose unsupported residual fragments, lie in the typical irregular replacement contact with the wall rock, and project in many places into intersecting joints. While evidence is lacking for conclusive proof as to the complete origin of these veins by replacement, this process is believed to have been dominant in their formation.

The vertical joint veins of the T and T_1 classes, however, show many phenomena suggestive of replacement. The evidence may best be considered by grouping the criteria according to Irving,[11] with slight modification.

Form.—The typical form of the Cobalt vein in transverse section is shown in Plate VII., *b*. The clean-cut walls and sharp contact of the narrow vein with country rock are suggestive of open filling rather than replacement. In many places, however, the vein is broader, reaching a maximum observed width of four feet. The ore spreads out into the rock in many tongues and its precise boundary with the wall is difficult of determination. A longitudinal section shows that the ore occupies short shoots abruptly ending in tongues. Therefore, though a vein may extend a thousand feet longitudinally it is by no means continuously mineralized. Such irregular, thick ore-shoots, and parallel, often imbricating and discontinuous veins seem to indicate possible replacement origin.

Relation of Veins to Rock Composition.—Both the form and the character of mineralization vary in the different rocks which, for the purpose of this discussion, may be regarded as Cobalt conglomerates and slates, Keewatin basic lavas, and Nipissing diabase. The conglomerate is silicious, the slates of intermediate composition and the latter two are similar and basic. A rich arsenide vein of average (four inches) thickness in the conglomerate becomes a poor arsenide vein of an inch or less in the slates; and upon entering the Keewatin or diabase it will frequently be of small dimensions and mineralized in great part by sulphides. Where the exceptions to these generalizations exist, the veins are found in strong continuous fractures. Though the rocks vary somewhat in physical, as well as chemical characteristics, the typical changes of veins in the different rocks are believed to indicate a definite effect upon precipitation of vein material by the character of the wall rock. Such an effect would be difficult of conception if the veins are open fillings; but would be expected in replacement.

[11] J. D. Irving, "Criteria for the Recognition of Replacement Deposits," Econ. Geol., vol. VI., p. 527 and p. 619.

Relation of Veins to Fissures.—Broad tongues of projecting veins have developed in joints which are quite tight (Plate VIII., *b*). Also in the Lake vein of the McKinley-Darragh Mine five closely spaced tight joints, lead to the vein which occupies continuously a space equal to that between the five joints. These cases are considered evidence of replacement.

Unsupported Fragments.—Angular fragments are common in the veins. Their shape might be thought to indicate brecciation and open filling, but in few of the cases observed is such an origin postulated. Where angular fragments with bedding have been rotated as in a *D*V vein of the McKinley-Darragh Mine, brecciation is certain, and like phenomena in other veins are to be correlated with this case. The great number of observations of fragments in vertical veins, however, indicate an origin by isolation of the angular piece of rock by means of replacement. Veinlets projecting from the main vein along cracks and joints may be seen beginning this isolation (Plate VII., *a,* and VIII., *a*). Bedding may be undisturbed and continuous as in the latter figure, and all stages from the beginning to the end of the process may be observed in the same vein. Elongated fragments are typical of a late stage of the process. As the fragments are often "unsupported" or isolated in the vein material (Plate VII., *a*), proof is conclusive of the operation of replacement.

Preservation of Rock Structures,—Preservation of structures in the veins is rare. Preserved bedding has never been noted though often replacement has taken place along bedding planes. A few cases of pseudomorphs of angular fragments by arsenides have been seen. In the conglomerate, however, boulders and pebbles are facile or difficult rocks for replacement. In Plate VIII., *d,* a pebble slightly faulted by a narrow veinlet is completely converted to calcite. The opposite of these relations is depicted in Plate VIII., *c,* where a boulder projects into a vein of niccolite. It is hardly likely that this boulder once projected into an open fissure, and the probability of the replacement origin of the vein is thus indicated.

Cases of selective replacement, however, are rare and usually

a vein cuts directly across a pebble, but remnants of such pebbles should be found in the opposite wall if the fissures have been merely opened and filled. In spite of the slight movement known to have occurred upon most of the fissures no such remnants have been observed. In the case of a nearly spherical boulder cut at the center by an arsenide vein about 1½ inches across, the parts were not displaced by the large vein, but were slightly faulted by an offshoot. Crystals of smaltite were scattered through the boulder near the veinlet. The remnants did not combine to make a symmetrically rounded form; part of each piece had been removed by replacement to make way for the vein.

Banding and Crustification.—Banding, not crustification, is common in the T and T_1 veins. It is more often unsymmetrical and where impenetrable gouge is the cause of the lack of symmetry the bands farthest from the gouge resemble those at the walls of symmetrical veins. These wall bands are of barren pink calcite, which constitutes the mineralization of the periphery of the veins, and this is probably of latest deposition. The inner band or core is of white calcite or dolomite, and is often edged by niccolite and smaltite. Where the pink calcite is absent, these margins of arsenide lie against the walls and, from their relations to wall and vein carbonates, they seem to replace the latter rather than the country rock. The bands are xenomorphic, are never of comb-structure, and very often disregard fragments. It is, therefore, believed they are due not to crustification, but to the successive change in solutions effecting replacement.

Marginal Relations.—Replacement relations at the contact of vein and wall can not be relied upon to prove the origin of the entire vein; for replacement of the wall and open filling of a cavity are frequently observed together. But where such relations are found accompanied by confirmatory data, they add weight to the evidence. Alteration of wall rock adjacent to veins is a feature of rare occurrence at Cobalt, but carbonates develop in places at vein-margins (Plate VIII., *b*). Complete crystals of arsenide are formed in the rock at the margins of veins (Plate VII., *c*). The irregular contact characteristic of replacement is well

illustrated in certain Nipissing veins. Such relations indicating replacement at vein contact are seen in the vertical veins of the district.

Conclusion.—Wherever significant phenomena have been noted in the T and T_1 veins, the indication has been that replacement rather than open filling was the process involved. All classes of replacement criteria have been observed widespread in these veins and, though few of the cases seem to offer conclusive proof, together the phenomena carry weight. It is, therefore, believed that the vertical T and T_1 veins, and thus the great preponderance of the veins of the district, have been formed in tight joints; that these joints were mineralized by solutions which caused the veins to grow outward from the fractures with certain definite marginal changes in character, and that the veins are due to the process of replacement.

Deposition of Arsenides and Carbonates.

Pressure and Temperature.—The narrowness of the veins, their comparatively small extension and the usual lack of alteration in the wall rocks indicate feebleness of the mineralization. High pressure during vein formation is to be inferred from the tight joints and the usual absence of open fissures. Coarse grained glassy quartz, dolomite with calcite, and the absence of chalcedony and opal, unite with the evidence of high pressure to exclude the veins from that class formed near the surface. The veins were no doubt formed at intermediate depths perhaps of several thousand feet; but, from the feeble action of the solutions, are believed to have been formed at temperatures low for these depths.

Solutions Changes.—The solutions, as shown by banding in the veins, were changing in composition. Those first acting precipitated white calcite, dolomite and iron-bearing dolomite. They thus were carbonate solutions containing calcium, magnesium, manganese, and iron, with probably CO_2. Other components may have been present at this stage, notably, cobalt, nickel, arsenic and minor amounts of lead, copper, bismuth, antimony and

sulphur, but these metals are believed to be characteristic of the second stage of mineralization represented by the marginal bands of arsenides in many veins.

The second stage of mineralization at many points, and possibly throughout the district, was by solutions carrying some carbonates of lime, magnesium, manganese, and iron, with CO_2, but composed chiefly of the metals enumerated above. What change in the solvents and in the volatile components took place with the advent of this second stage can not be inferred.

The third and last stage of original mineralization was by solutions depositing calcite with minor amounts of sulphides. In solution no doubt were carbonates, principally of lime, some silica, iron, lead, zinc, copper and sulphur. Small amounts of silver may have also accompanied the second and the last solutions.

Local Stress and Precipitation.—That such solutions, even in the stages presumed and penetrating a network of flat, steep and vertical structures simultaneously, should have mineralized these structures in the distinctive manner of barren flat veins and steep and vertical arsenide veins, must cause some surprise. The earlier consideration of the origin of the structures has, however, made clear that the vertical fractures and the loci of arsenide bodies on steep structures, were probably formed under conditions of tension. The fractures whose veins are typically barren of arsenides were caused by compression. At intersections of compression and tension fractures, intermediate conditions prevailed. As the forces causing the fractures are believed to have persisted during mineralization, it is thus probable that the precipitation from the solutions forming the veins was governed by the stresses upon the vein joints. At all times compression permitted only barren calcite, dolomite, quartz and sulphides to be precipitated upon the flat structures and upon the great part of the steeply inclined. Where, locally, tension acted upon the steep structures and upon the vertical joints, arsenides, calcite and dolomite were deposited. Under intermediate conditions mixtures of the two characteristic types of mineralization resulted.

Stress is known to have little effect upon equilibrium in solu-

tions except when volatile components are present;[12] but in such cases it exercises great influence upon solution and precipitation. CO_2 was, of course, probably present in the vein solutions of Cobalt; but whether this gas under different conditions of stress affected the solubility of arsenides and sulphides, whether another volatile component may have been active in this way, or whether the precipitation was caused by other factors of the solution, are questions rendered unanswerable by the great complexity of the solution systems and the present obscurity of the whole subject.

Deposition of Silver.

Former Opinions.—A stage later than the arsenide-calcite mineralization has been generally postulated for the origin of the silver of the Cobalt veins. Miller[13] concurred with Campbell and Knight[14] in ascribing the silver to an addition to the arsenide veins later than a period of fracturing of these veins. Earlier publications[15] upon the district had suggested such an origin of the silver without offering the careful microscopic study of Campbell and Knight. S. F. Emmons[16] has proved conclusively the late deposition of the silver and recently Bastin[17] has presented further excellent microscopic evidence strengthening the earlier conclusions, and indicating the replacement of ferruginous calcite and arsenides by silver. The present investigation has in every way confirmed the past results.

The presence of native silver, at times containing antimony and approaching dyscrasite in composition, in veinlets cutting arsenides and iron-bearing dolomite and calcite in the veins, the

[12] John Johnston, "Pressure as a Factor in the Formation of Rocks and Minerals," *Jour. Geology*, vol. 23, 1915, pp. 736–741.

[13] W. G. Miller, "The Cobalt-Nickel Arsenides and Silver Deposits of Temiskaming," Ont. Bur. Mines, vol. 19, pt. 2, 1913, p. 12.

[14] W. Campbell and C. W. Knight, Econ. Geol., vol. 1, 1905, pp. 767–776.

[15] C. R. VanHise, *Can. Min. Inst. Jour.*, vol. 10, 1907, pp. 45–61.
R. E. Hore, *Can. Min. Inst. Jour.*, vol. 11, 1908, pp. 275–286.
A. E. Barlow, *Can. Min. Inst. Jour.*, vol. 11, 1908, pp. 256–272.

[16] S. F. Emmons, "Types of Ore Deposits," Pub. by Min. and Sci. Press, San Francisco, Cal., 19111, pp. 140–156.

[17] E. S. Bastin, Econ. Geol., vol. 12, 1917, pp. 219–236.

deposition of rich plates and wedges of native silver and dyscrasite upon fractures slightly displacing the veins, and the precipitation of thin leaves of silver upon fractures often flat and barren of arsenides, unite with widespread similar observations in sustaining former conclusions. They also offer conclusive proof of the origin of native silver in the Cobalt veins by a stage of ore deposition later than both the arsenide mineralization and a subsequent period of slight fracturing.

The matter of chief interest in the present contribution is the age and character of the silver forming stage. The Canadian geologists implied in their first discussions of this matter that the silver was a later addition to the contents of veins from the same source as that of the nickel and cobalt arsenides. Emmons,[18] however, advocated the origin of the rich silver shoots by downward secondary enrichment and offered some strong evidence sustaining this conclusion. Miller[19] seemed in the fourth edition of his report to agree to the enrichment theory as he said that "the silver solutions working downward beneath the sill . . . lost their silver contents . . . before a great depth was reached." Bastin,[20] with the hesitation natural to one who had not visited the field of his microscopic research, implied the operation of downward enrichment in the Cobalt veins. Thus the late tendency of opinion regarding the rich silver ores of Cobalt, and, indeed, those of other silver districts, is to ascribe their origin to superficial processes; but the evidence of such origin is not conclusive.

Objections to Supergene Enrichment.—The theory of the origin of the silver in the Cobalt veins by downward enrichment as advanced by Emmons is based (1) upon the presence of later fractures often filled with silver, (2) upon the statement that "the rich ores are not confined at Cobalt to any single mine, or (3) to the veins in any one formation," (4) upon the fact that bonanza ore often changes suddenly to low grade ore; and (5) upon his inference from the deep erosion to which the rocks of

[18] *Op. cit.*, p. 153.
[19] *Op. cit.*, p. 13.
[20] *Op. cit.*

the district have been undoubtedly subjected, that the veins had formerly a great vertical extent. Later development of the mines and the recent opportunities for thorough investigation have thrown more light upon these matters. (1) The presence of later fractures, which are, however, believed to be but slightly subsequent to the vein fractures, is amply confirmed as is the deposition of silver upon them. (2) The rich silver ores of Cobalt are, of course, not confined to one mine of the district. The great part of the production of the district, however, has come from perhaps 15 mines, which are clearly grouped into three districts, those of Cobalt Lake, of Kerr Lake, and of the south, and which are related to definite early structures and not to the widespread development of late fractures. (3) More than ninety per cent. of the production of these mines, probably has come from one geologic formation, the Cobalt conglomerate, and the relatively few cases of rich veins in other formations are seen to be due to peculiar and unusual structural causes. The typical rich ore has, therefore, contrary to Emmons's statement proved to be essentially confined to one formation. (4) The sudden change of bonanza ore to poor ore or barren vein is characteristic of the Cobalt veins; but it is to be found usually at the lower extremity of the vein. Such a case determined by a bed of slate was described by Emmons.[21] Sudden variations in the values of veins are not confined, however, to enriched ore deposits. They may be caused in any type of mineralization by sudden changes in the conditions determinant of deposition. Lastly (5) the essential of Emmons's theory, the great vertical extent of veins, perhaps low-grade, in the district is disproved by the exploration subsequent to his work. The veins typically extend upward 200–300 feet as a maximum above the Huronian-Keewatin contact, they outcrop as roots of former veins, deep cut, only along the outcrop of this contact, and even there they are identical in character with deep-lying veins in the district (Fig. 17). It is very doubtful if any vein exposed at the present surface in the district has been

[21] S. F. Emmons, "Types of Ore Deposits," Pub. Min. and Sci. Press, San Francisco, Cal., 1911, p. 151.

reduced in vertical extent more than 300 feet, and the great number have been subjected less than this to erosion.

Many other considerations, both chemical and geological, constitute insuperable objections to the theory of the origin of silver in the Cobalt veins by downward enrichment. Bastin[22] argued well that if downward enrichment were an important process at Cobalt, it would take place by acidic sulphate solutions carrying silver and iron, and by the bringing of these solutions into contact with the typical minerals of the Cobalt ores. Such solutions, however, can not be formed in quantity by the oxidation of the typical Cobalt veins. These veins contain rarely pyrite and seldom sulphide of any metal. The vertical or common silver-bearing veins are essentially free of sulphur. Therefore, the extensive formation of sulphates and of soluble silver salts is not to be expected during oxidation. The examination of oxidized veins confirms this deduction as, in such ore, leaves of native silver are found unaltered in a matrix of oxidized arsenates from which often much of the calcite has been dissolved. The silver, under oxidizing conditions, is the most stable constituent of the vein.

Moreover, oxidation is a very superficial phenomenon in the district and is all post-glacial. The water level is high and arsenates are found in new mining development only a few feet from the surface. Though most of the outcropping veins have now been stoped, no records of extremely high values or of other indications of enrichment at the water level have been noted. Of more importance, however, is the relation of the ores to a possible former zone of oxidation since removed by glaciation. A water level below such an oxidized zone must have been higher than at present as no remnants of the oxidation are at present found in the district. Therefore, if the ores are to be regarded as due to downward enrichment during the continuance of such conditions, they must all have been precipitated below the water level, and often relatively deep below this level. Circulation then must have been as it is to-day sluggish on the veins and joints and more

[22] *Op. cit.*, p. 236.

swift upon the faults with their broad crushed zones. Yet silver deposition has not taken place along such fault fractures. The requirement of enrichment deep below the water level is alone distinctly unfavorable to this origin for the ores. Below the water level diffusion of metallic salts lowers their concentration and carries them away from the veins from which they were derived. In the many cases of downward enrichment observed and described in recent years few, if any, have presented evidence of more than feeble enrichment far below the water level.

A final objection to the downward enrichment theory for the Cobalt ores is the essential barrenness, and often entire absence, of unoxidized veins above many rich ore-shoots. Barren calcite veins at the surface have been followed down to typical silver ore. Many blind veins have been recently developed. Such veins have carried silver 450 feet below the surface and in one case 1,600 feet under Keewatin and diabase. The presence of rich ore due to downward enrichment 500 to 1,500 feet below the water level and upon veins and fracture which do not penetrate the present surface much less a former higher surface, is unlikely.

Extent of Supergene Enrichment.—Downward enrichment, though it can not be postulated for the origin of the economically important ore, is probably active on a small scale in the district. Slight amounts of native silver may be precipitated in the manner described by Bastin. Minute crystals of ruby silver (proustite) are often to be observed imbedded in the gouge of faults where circulation of water is less restricted. These crystals may well be of supergene origin; but, as proustite has not yet been proved chemically to be deposited from cold, vadose solutions, even this instance of supergene silver deposition must be regarded with some doubt.

Evidence for Hypogene Enrichment.—Evidence not only negative regarding downward enrichment but positive regarding the origin of the silver of the Cobalt veins as a last phase of the original mineralization of the veins is available. Suggestive of more intense conditions than those of supergene solutions are the replacements of wall rock by silver observed frequently, but in an

especially striking case in the vein in diabase of Plate VII., *a*. The vertical variation of values is, however, of most significance. The ore characteristically decreases in value upward from its lower extremity, usually on a fault. Sudden increases in richness may take place at cross fissures typically flat; but at the upper limit of the ore-shoot low grade silver-bearing arsenide grades through barren arsenide into calcite. At the lower limit sudden decreases in value may be due to the intersection of beds of slate, and to the change of rock to fine graywacke or to the basic Keewatin or diabase. In such case the arsenide vein narrows or disappears and values die out. Though somewhat more irregular than the arsenide areas, the fan-shaped ore shoots of silver upon the veins are concentric with those of the arsenides, decrease similarly in intensity of mineralization toward the periphery, and often do not extend so far outward upon the vein as those of the arsenides (Fig. 17). Such relations are excellent indication of the continuance of the early processes of mineralization.

Hypogene Sulphate Solutions.—Palmer and Bastin[23] have discussed the chemistry and the mode of deposition of native silver in the Cobalt ores and have demonstrated that the precipitation might take place from acidic sulphate solutions carrying silver and iron. It is by no means inconceivable that such solutions may have been of primary origin,—hypogene rather than supergene. Many data from widely separated regions unite to offer indication of a possible final stage of hypogene mineralization by sulphate solutions. The deposition of alunite at Goldfield, Nevada, stated by Ransome[24] to be caused by oxidation from the admixture of atmospheric waters with igneous emanations was undeniably a late concomitant of typical mineralization of igneous origin. Deposits of alunite at Marysville, Utah, are due to igneous activity. The presence of anhydrite in certain contact metamorphic deposits is indicative of sulphate emanations

[23] Chase Palmer and E. S. Bastin, Econ. Geol., vol. 8, 1913, pp. 140–170; vol. 12, 1917, pp. 207–218.
Chase Palmer, Econ. Geol., vol. 11, 1914, pp. 664–674.
E. S. Bastin, Econ. Geol., vol. 12, 1917, pp. 219–236.

[24] F. L. Ransome, Prof. Paper 66, U. S. Geol. Survey, 1909.

from igneous bodies. Alunite has been observed by the author as a mineral deposited by contact metamorphism at Santa Rita, New Mexico, and is in the Morenci district, Arizona, of possible igneous origin. Finally his study of the copper ores of Morenci, Arizona, Nacozari and Cananea, Sonora, and other copper deposits has indicated the probability that in these deposits the structures of late primary copper sulphides, so similar to those of the supergene copper sulphides, are due to similar conditions of origin—namely, to deposition from sulphate solutions. The significance of such a stage, if proven, is great, and though data is quite insufficient either to warrant the assumption of hypogene sulphate solutions in the origin of ore deposits in general or of those of Cobalt in particular, the possibility of such a stage should be recognized.

Conclusion.—The conclusion is, however, reached that downward secondary enrichment has been essentially absent as a factor in the deposition of silver in the Cobalt ores and that the silver of the veins is due to the last stage of the primary mineralization.

Origin of the Veins.

Source.—The ultimate source of the metals of the ores is a matter of first interest in the genesis of the veins of the Cobalt district. The igneous origin of these metals is universally conceded and the igneous rock first to suggest itself as a parent of the mineralization is the Nipissing diabase. The diabase, however, had solidified with but slight segregation, had been folded, faulted and jointed by forces entirely unconnected with its cooling and thus had been in place a certain length of time before the formation of the veins. It seems, therefore, unreasonable to attempt to connect the origin of the veins with hydrothermal activity from the diabase itself. The metals may, however, have been derived from the cool diabase by leaching, but if this leaching were by circulating waters alteration along fractures and joints throughout the diabase would take place. No such phenomena have been observed. Other great igneous bodies of post-Keweenawan age with which the mineralization might be con-

nected do not intersect the surface of the district, and have not been noted in Canada.

The low temperature inferred for the vein forming solutions indicates, however, that, if the veins are due to igneous emanations, the waters offspringing from the intrusive mass have travelled far before accomplishing deposition. The presence of the parent igneous body at the surface is, therefore, hardly to be expected; but rather the possibility of a deep lying plutonic rock is to be considered.

A succession usual in igneous irruption is intrusion, pneumatolitic action and finally the production of veins,—all in a sequence of lessening intensity. Aplite and granite dikes following the intrusion of diabase complete, at Cobalt, the first two stages. Nothing could be more in accordance with the generalizations from many mining districts than that the final stage of irruption should be characterized by the expulsion upwards through all available fissures of highly heated, mineralizing solutions under great pressure.

Hypothesis of Origin.—During the development of the faults no doubt, extending to great depths, channels of escape were offered solutions; they progressed upwards, and cooled during the ascent. Upon reaching the zone of present day observation, they were perhaps moving more slowly; but still under high pressure, were cool, probably of a temperature higher than 100° C. but distinctly lower than 200° C., and, as shown at the greatest depths upon faults penetrated in the district, deposited essentially barren veins of calcite.

When the solutions reached the strong zones of flat fractures at the Keewatin-Huronian contact, they escaped widespread from the main channels. Encountering the few strong fractures near the Keewatin—diabase lower contact, in the diabase and at the upper Keewatin—diabase contact they were, in part, deflected.

On the shear zones the solutions could not proceed far, for these fractures are confined to the limbs of folds. Thus concentration of solutions and consequent ore deposition did not take place as might be expected by deflection of the circulation into

anticlinal arches. Further escape was, however, offered by the vertical fractures. As such fractures are believed to have been tight at the time of mineralization, some difficulty may be encountered in the conception that solutions would have ingress into them. The probability of high pressure and perhaps a great content of volatile components of the solutions, the form of the minor channel, a cul de sac, and the very compact nature of the rocks bounding the fractures lends weight to the view that solutions would penetrate the vertical joints. Capillarity, or surface tension, no doubt assisted pressure in forcing the mineral bearing waters slowly in a direction usually upwards, but at times downward, along the closed fractures. Deposition of the dissolved burden by replacement was accomplished in a manner different from that upon the faults and shear zones because the compressive stress characteristic of the latter fractures was absent. Slow movement, diffusion of dissolved salts from the channels upward to the point of deposition, and perhaps even the thinness of the solution films may have assisted in precipitation. The solutions now relieved of their excess burden of solute proceeded farther along the fractures until dissipated in the upper strata.

This hypothesis is sustained by the facts that

1. The usual irruptive sequence is earlier than the veins.

2. The inferred coolness of the solutions implies a deep-seated source.

3. Widespread occurrence of veins at Cobalt, South Lorrain and Gowganda has similar implication.

4. The segregation of economically important veins is in accord, first with deeply penetrating fractures, and second with zones of shear diverging from the former.

5. The most important of these zones, the Cobalt-Keewatin contact, is, where present, the first to be met in ascension on faults in the district.

6. The veins lie near the diabase (800 feet) due to the shear zones or contacts lying in this position.

7. The banding and succession of the veins suggest the changes in composition typical of ascending circulation.

CONCLUSIONS.

Geology.

1. The Cobalt series is of stream origin.
2. Its base was a topography of slight relief.

Structure.

1. The rocks of the district were subjected to deformation by forces of compression upon two normal axes.
2. The structures developed are essentially contemporaneous.
3. The major fractures of economic importance were formed in definite relation to faults and folds.
4. These fractures were probably due to local tensional stress.

Veins.

1. The veins are but slightly faulted, and are about of the same age.
2. They may be classified by
   (*a*) Attitude,
   (*b*) Certain structures determining ore shoots.
3. The mineral content is influenced by the type of joint on which the vein was formed.
4. The veins are predominantly due to replacement.
5. During an early hypogene stage calcite, dolomite, arsenides and sulphides were deposited.
6. During a late hypogene stage silver was deposited.
7. Supergene silver deposition is essentially absent from the veins.
8. The veins were probably formed by hot waters, of deep seated, possibly magmatic, origin.

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DIFFUSION IN VEIN-GENESIS AT COBALT.

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It is no less a convenience in geological as well as other kinds of work, to have standard tools and materials. It is therefore a great temptation for geologists to accept certain standard theories as legitimate working tools, which they need no longer hold in question, but may henceforth take for granted. And so it has come to pass that processes of ore-formation have been standardized and listed, to the exclusion of what may yet be recognized as one of the most potent genetic processes. In the silver deposits at Cobalt, the writer believes he has found an example of the operation of this unrecognized process, worthy of being described as a type case.

Long ago the idea of "lateral secretion' as advocated by F. Sandberger was condemned in geologic opinion. The verdict was probably just in respect to the letter, but unjust in respect to the nucleal idea of his conception. In Geologische Diffusionen,[2] R. E. Liesegang has indicated the ground upon which the decision against lateral secretion will probably be reversed. Posepny[3] quotes Sandberger as saying:

> The theory of lateral secretion was conceived in this sense only, that the material for the filling of veins is derived from the country rock through gradual leaching by seepage-water, which brings the dissolved substances from both sides of the fissure, where it is then converted by chemical decompositions into insoluble gangue minerals and ores, and so deposited.

The error in this theory lies in the assignment of the task of transportation to circulating water; and the reversal of the decision against it will be based upon a recognition of the potency

[1] Companion paper to that by W. L. Whitehead in this number.

[2] Reviewed by Adolph Knopf in ECON. GEOL., Vol. 8, No. 8, Dec., 1913.

[3] "The Genesis of Ore Deposits," Ed. 2, 1902, p. 57.

of diffusion to perform that task without the aid of movements of water. In all likelihood, it will yet be adequately demonstrated that much more often than is now supposed, ore deposits originate through the migration of ore materials from country rock in or adjacent to which the deposits lie.

The efficacy of diffusion to produce many geological phenomena has already been recognized. It has been assigned an important rôle in metamorphism, in banded weathering, and in certain ore-forming processes; but either by silence or direct imputation it has been denied recognition in its true rôle as a prime agent in the formation of all metasomatic deposits.

Before presenting the small array of evidence which has a direct bearing upon the problem, it will, perhaps, be best briefly to set forth the main thesis, which is as follows:

1. The cobalt-nickel-silver ores of the Cobalt District were derived by diffusion and metasomatic fixation from the sill of Nipissing diabase with which they are associated.

2. They were deposited essentially in their present form below the groundwater level, not by circulating solutions, but by migrant ions traversing virtually stagnant or slowly circulating aqueous solutions, from all parts of the adjacent diabase, to such favorable seats of deposition as were accessible in the neighborhood of its margins.

3. Mineral-laden water filled all the pores, joints, and fractures of the diabase and its neighboring rocks; and through it moved the ions of vein material, at a temperature considerably below the melting point of the diabase, and at a pressure of several thousand feet of hydrostatic head. These ions were not capable of combination and precipitation without the help of an external agency; this consisted in catalytic influences or obscure metasomatic reactions of a kind which could take place only in rock relatively free from stress in one direction, as that must have been, which lined the sides of vertical tension joints lying parallel with the chief lateral stresses of the locality. The effect of these reactions of replacement, although virtually grain-for-grain as is understood by the term *metasomatic,* was to send into solution

the aluminous and ferrous silicates composing the wall rocks, and to fill the vacated space grain-for-grain as it developed, with the ore minerals. The first rock to be thus replaced was that under least stress on the immediate walls of the indicated joints. The joints being tight, there was virtually no opportunity for crustification. The replacement extended outward from the plane of its inception, the widening vein always being so firmly frozen to its walls that aqueous solutions would move along it often with less ease than elsewhere through the wall rock.

Because the writer has been limited to the industrial phase of this study, and in part because of its inherent character, the support of these propositions must be chiefly in the nature of evidence-taking rather than proof. Therefore the following evidence is offered only as a statement of the chief considerations which weighed in his mind to incline him to accept this theory of genesis.

(*a*) The commercial ore bodies are found in the diabase itself, and in the Keewatin and Cobalt Series (called the "conglomerate"), which it intrudes. In the diabase and Keewatin the ore bodies lie within 350 feet of the upper and lower margins of the diabase; but in the conglomerate commercial ore bodies lie as far away as 550 feet. Of all the silver veins that have been mined in northern Ontario, whether in the Cobalt District, Gowganda, South Lorrain, or in Casey Township, none have carried commercial ore bodies in contraversion of this rule; and this applies to more than 200 veins. Rich ore has been found in the Beaver Mine in the Keewatin and diabase on the lower margin of the sill, at a depth of 1,600 feet, which is virtually the same depth below the present watertable. The writer regards the ore bodies as a marginal phenomenon belonging to the diabase, and coexistent with it. As far as exploration has gone this is well indicated, even in respect to non-commercial bodies of silver, smaltite, and niccolite in calcite veins in almost every locality where the diabase is found, or has been eroded away. This relationship, therefore, is offered as an evidence that the cobalt-nickel-silver ore has emanated from the diabase itself, rather than from its mother-magma.

A refutation of the theory of vadose origin for these deposits may be omitted here; but the idea of their origin from ascending juvenile waters must receive attention. If this latter hypothesis were correct the ore materials must be assumed to have ascended along the major fissures of the district, which most likely are quite deep-seated, and were available as channels of escapement at the time of mineralization. In view of that fact it is hardly supposable that the ore materials would have reached their present resting places by traversing the unfractured or discontinuously fractured rock for so great a distance, in preference to the more open channels. But the major fissures have not been found to be mineralized, and probably are not, beyond the stated limiting distances from the diabase. Furthermore, the occurrences of the vein minerals in commercial and non-commercial quantities are widespread, and without any notable reference to major fissures, often, in fact, demonstrably at distances from the fissures or possible deep-seated channels of distribution other than the diabase contacts themselves, of more than 1,000 feet. This holds for many of the richest veins of the district, notably at the Kerr Lake, Temiskaming, and Beaver Mines. In these cases, but even more conspicuously in many non-commercial deposits, in order to have come along a margin of the diabase from a known major fissure, the ore materials would have had to traverse several thousand feet of undulating and nearly flat contact to reach their seats of deposition, a fact which seems to weigh heavily against the theory of ascending mineralization.

It is necessary here to explain that the term *major fault* is properly applied only to faults of the N.E.-S.W. or the N.W.-S.E. systems, with one or two possible exceptions in the E.-W. system, which includes what are spoken of as the side-thrust faults. The two former systems are conceived by the writer to be very old and deep-seated; but faults of the last named system are, most likely, relatively shallow. They are found in all sections of the district, and consist of vertical or nearly vertical fractures upon which the chief component of movement has been horizontal. In this system 64 Fault in the Nipissing Mine and the chief vein

fissure in the O'Brien Mine are conceded to be fairly deep, although even the latter of these has not materially dislocated the Keewatin-diabase contact. In the Kerr Lake region no great throw has developed on any of these faults, and the same holds for the Temiskaming and Beaver Mines. It is particularly important to note in this connection that in this region a fault in the Keewatin basement formation must have a large throw in order to have a great extent.

(*b*) Probably it will not be disputed that the ground water fills all fractures and rock pores below the watertable to variable depths, even if barely sufficient in the rock pores to yield water in the closed tube. This does not imply that dry fractures are not to be found in mining, since pumping operations from deep sumps may account for that phenomenon. In other cases the dryness of fractures found in deep mining might be accounted for by the recent origin of the fractures. Also short fractures are quickly drained.

If a magma comes to rest in such an environment and exudes juvenile waters, they will almost certainly become commingled with the groundwater, whose circulation has been stimulated by the accession of heat from the magma; and there will be an upward circulation started in the neighborhood of the intrusive mass, following the most accessible channels. However, if there are no continuous open channels leading upward, the escape of the heated solutions will be very difficult, and perhaps at too slow a rate to even carry heat a great distance.

Fuller says:[4]

> The results of drilling . . . as well as studies of deep mines, show that . . . water does not commonly exist in the rocks under great pressure.

Relativity and time are often overlooked in research; but they are not overlooked in the processes of nature. It is doubtful whether data could be obtained to prove Mr. Fuller's assertion. If a deep diamond drill hole is put down from the lower dry portion of a deep mine, it might remain dry for the lifetime of the

[4] U. S. Geol. Surv. Water Supply Paper No. 160, p. 64.

mine without indicating that an open space at that depth would not fill with ground water. Also if a water-filled fissure at a great depth does not yield water under apparent pressure when tapped by a drill hole or a mine working, that does not indicate that the water in the fissure is not under immense pressure; for the rate of flow is not an absolute measure of the pressure, for experimental purposes, when it is so slow as to require geological time for its estimation. Water filling a deep fissure, tapped by a diamond drill hole, might be under a hydrostatic head of thousands of feet and yet not fill the hole in the course of a decade; for water in such a chamber can flow out of the chamber only as fast as it flows in.

Where the zone of fracturing begins to merge with the zone of rock-flowage, it is conceivable that the tight fractures produced by a sudden deformation might remain dry, or at least incompletely filled with water for many years, and yet ultimately become filled under high pressure through the slow accession of water from capillary openings. Any person familiar with deep mining operations may often have seen cross-cuts in "dry ground," so dry that dust from the drills floats in the air like smoke. After blasting, when the fresh face is examined, only dry fractures are found and no signs of moisture. Yet at some distance back from the face, where the fractures have been exposed by the cross-cut for many days, the dust which has accumulated upon the back and walls will show dampness at these fractures. This is as likely to be seen on the sides near the floor of the cross-cut as on the back. Such workings as these are called "dry," and for all practical purposes they are dry; but geologically they are full of water, perhaps under a hydrostatic head of thousands of feet. The shock of the blasting probably emptied the fractures close to the face; and several days or weeks are required for the loss to be compensated, and enough water gained to keep pace with the relatively rapid evaporation which goes on in a well ventilated mine. It may even be that the rate of accession of water will not keep pace with the rate of evaporation; and the fracture although yielding water will show none.

This is a rather negative line of argument, but as refutation it is called for by the arguments of those who contend that the ground water does not penetrate far below the watertable.

The purpose of the foregoing argument has been to indicate that water may fill all open spaces to a considerable distance below the water table, but that even according to those who believe in the flow of underground water as a potent agency in the formation of ore deposits, its flow is most apt to be slow, at a considerable depth below the surface. But this portion of the general argument is not complete until attention has been called to the fact that if it is difficult for the groundwater to circulate downward in the lower portion of the zone of fracture, it must be, for the same reasons, equally difficult for juvenile waters to ascend freely or in any greater volume. Where the groundwater can not descend, juvenile waters can not ascend.

(*c*) Lindgren[5] points out that

> In subcapillary openings the attraction of the molecules extends from wall to wall, and this class includes tubes smaller than 0.0002 mm. in diameter, and sheet openings smaller than 0.0001 mm. in width.

He also says:

> In subcapillary openings the water is held firmly as a film, glued to the walls by adhesion. There is no free water, and the flow is practically nil.

Undoubtedly this is true; but if it is admitted, then how can olivines and feldspars be altered to serpentine, limonite, saussurite, kaolin, and so on, along fracture surfaces and cleavages in firm rocks taken from far below the surface? Have substances been added and withdrawn to effect these alterations by a circulation of water through those microscopic openings? The "Liesegang rings" explained by Ostwald, and the banded weathering explained by Knopf, were attributed to the operation of diffusion. Many phenomena, as the banding in agates, pseudomorphism, and metamorphism, have been assigned by various geologists to diffusion; and there seems to be no objection to assigning to the same process the phenomena of mineral altera-

[5] "Mineral Deposits," McGraw-Hill, 1919, p. 31.

tion along internal fractures and cleavages. If circulation is required to produce ingress and egress of material, why can it not be a circulation of ions—the solute rather than the solution?

Fick, Soret and others have given some attention to chemical or *laboratory* diffusion, and have worked out laws to the effect that the rate of diffusion is proportional to the concentration and inversely proportional to the distance travelled, also that heat accelerates diffusion so that the solute tends to concentrate in the cooler portion of the solvent; but diffusion in films may be a different matter than diffusion in chambers; and with the introduction of geological time, effects may be produced, the magnitude of which goes far beyond any hints coming from the laboratory.

It is difficult at first to conceive of diffusion as operating on a scale commensurate with that required for the formation of some of the immense metasomatic or impregnation deposits, which lie at a distance from the nearest igneous rock. However, it is more difficult to conceive of the ore material being carried to the point of precipitation and there being deposited by a current of water, however small, wending its way among the capillary and subcapillary openings which lie among the grains of a firm rock. All the reported analyses of mineral-bearing waters which flow from springs indicate that they are exceedingly dilute solutions. If one studies a wide breast of ore in a metasomatic deposit, and realizes the amount of water from which it must have been deposited according to the circulating water idea, it will be difficult for him to conceive of that amount of water as having ever circulated among the pores of the firm wall rock, or along the tightly cemented walls of the ore body or the discontinuous veinlets which compose it. In the case of a crustification deposit, where all the mineral deposited was laid down on the walls of a gradually narrowing open fissure, transportation by diffusion would be more difficult and less necessary to show evidence of; but in a deposit where the space now occupied by ore was never an open chamber, and metasomatic replacement was the means of its origin, whatever circulation served to bring the vein matter,

and remove the walls to make room for it, must have traversed the contact between the vein and its walls, or between each mass of ore and its individual walls. The openings in such cases must have been subcapillary, if the evidence of the microscope is to be accepted. That circulation, if of an entire solution, must surely have proceeded with extreme difficulty and have consumed an exceedingly long time; but if the circulation was of streams of ions, it would have been much more subtle, because of the continuously undiminished actuating force, and might have proceeded with much greater speed, also requiring no greater concentration of the solution than that of ordinary hot spring waters.

Wherever deposition of mineral has taken place by other means than crustification, sedimentation, or segregation, it must have occurred chiefly by the agency of diffusion. Very likely those who take issue with this statement will do so on the ground that although local diffusion may be admitted in such cases, it can not be assumed that the major transportation was by that means. The answer is a partial concession. Undoubtedly mineral-bearing water circulates in the deeper portion of the ground-water; but while it is circulating slowly along the avenues of transportation to the places of deposition, there must be going on within it a more rapid circulation of ions, by diffusion, causing an accumulation of metalliferous ions and molecules at the seat of deposition vastly greater than moving water could ever obtain. This allows, however, that in some cases the circulation of water may have been virtually nil. Heat would be an effective stimulant to the circulation of both water and ions; for capillarity is decreased and diffusion is increased with rise of temperature; but this affects the problem only in the sense of reducing the size of the openings to which the above principles apply, or in shortening the time required for the formation of a deposit, not altering the relations between convection and diffusion.

The mechanisms of diffusion, metasomatism, and catalysis are little understood; yet they are involved in the phenomena of vein formation in such a manner as to compel an effort to circumscribe them as well as possible, in the present discussion. Dif-

fusion applies to substances in an ionized condition, and tends to distribute the ions uniformly throughout a solvent of uniform temperature. Thus if ions are being withdrawn from a solution at any point there will be a general migration of the solute toward that point, to maintain the uniformity of distribution; and by direct and indirect routes, the ions will move from the point where they are entering the solution, say, from a dissolving substance, to that at which they are leaving it, say, where precipitation is going on. In consequence of this rule, it follows that if ore is metasomatically replacing wall rock, there will be a flow of metalliferous ions to the seat of deposition, and a flow of the various ions derived from the wall rock, away from that point, to be distributed throughout the solvent. The solvent in this case is, of course, the entire body of groundwater, in all its devious ramifications through the rock pores and fissures.

Field and microscopic studies indicates in many instances that grain-for-grain replacement of rock by ore minerals is volume-for-volume and not weight-for-weight nor molecule-for-molecule. If metasomatism is to be understood in this last sense, then probably the word will have to be dropped from the vocabulary of geologists, or at least from that of ore deposits, its applications in geological phenomena being very limited. Grain-for-grain will answer all cases, and will permit the word to be used for cases which are clearly volume-for-volume, and which happen to embrace all the replacements which have come under the writer's observation. This would seem to imply that the process is really less chemical than physical, and that chemical reactions scarcely need be looked for, which involve the ore minerals and those of the wall rock in the same equation. However, this is not offered as a dogma.

In his recent studies of the Porcupine gold ore deposits,[6] the writer found that in typical situations, quartz veinlets were bordered by a thin film of ferro-dolomite. The microscope showed that the meta-andesite schist constituting the wall rock, which consisted of a few feldspars, a few areas of secondary quartz,

[6] *Canadian Mining Journal*, Volume 36, No. 19.

some chlorite, hornblende, leucoxene, considerable sericite or paragonite, magnetite, and ferro-dolomite, was indiscriminately replaced by coarsely crystalline ferro-dolomite vein matter, which, in turn, was replaced by vein quartz in such a manner as to preserve in the latter a rhombohedral boundary against the former. Thus, the replacement of the wall rock by vein quartz proceeded by stages. The first stage, or ferro-dolomite replacement, was indiscriminate with reference to the minerals of the meta-andesite schist; but the second stage, or quartz replacement, was selective in the sense that it followed the molecular structure of the carbonate. This might seem at first hand to indicate molecular or chemical replacement; but on second thought it must be recognized that dissolution might have followed those lines, and physical replacement merely have filled the vacated space as it developed.

This is the writer's conception of the metasomatic process as it operated at Cobalt. Here there was no such obvious progression by stages; yet there might have been a somewhat analogous sequence, less easy of recognition. The veins of Cobalt are not characteristically bordered by what appears to have been an intermediate stage of replacement; but there seems to have been a rough succession of replacement operations, which give the illusion of successive periods of mineralization.

The veins at Cobalt appear to have been formed with reference to the stresses which existed in the walls of certain vertical joints, in the sense that where the walls were most completely relieved of stress, the mineralization was most rich and copious, consisting of silver and the arsenides; and as the stress increased the mineralization decreased, consisting in typical cases of calcite. In cases where calcite and arsenides exist together, the former never has replaced the latter; and the relations are usually obviously the reverse. In the same manner, silver appears never to have been replaced by the arsenides, but often to have replaced them, as along fractures. Thus the rough sequence seems to be calcite, cobalt and nickel arsenides, and silver. Often arsenides or silver appear to have replaced the wall rock directly; but these cases

may represent instances where the preceding stage of replacement has been replaced in its entirety, leaving no trace of its former existence.

If the replacement was physical and not chemical, the sequence may relate rather to the physical condition of the replaced or passive substance as compared with the conditions demanded for deposition by the approaching or active substance. For instance, calcite may be a more favorable medium for smaltite to deposit in than greywacke or diabase; but in certain local situations, one of the latter might serve just as well as calcite. If the replacement was grain-for-grain rather than molecule-for-molecule, and was vitally related to the stresses in the fissure walls, it may have been the result of a catalytic influence. Perhaps it is only dealing in mysteries to invoke the aid of catalysis in this emergency; yet there was certainly such an intimate relationship between the dissolution of a grain of wall rock and the deposition of a grain of ore that a grain of the latter could not go out of solution unless a grain of the former made room for it by going into solution. It may be, however, since stress is involved, that the whole matter resolves itself into a sequence of relative stabilities of certain substances under conditions of molar and molecular stress in this manner; suppose that along a vertical joint the rock-flowage tendency is overcome in the immediate walls by a direct gravitative thrust downward along the fissure, and also by a lateral thrust along it, so that the resulting tension normal to gravity and to the lateral thrust barely parts the walls; and they just touch each other, but are relatively free from normal compression. Under these conditions, the joint and its walls are filled with solutions containing the ions of dolomitic calcite, smaltite, niccolite, and silver, along with other unknown substances. There is a tendency for the various rock particles in the conglomerate or meta-andesite schist walls to be forced toward the fracture; this they can do by going into solution. There is also a tendency for the ions already in solution to go out, since they are capable of combining to form substances which are stable and insoluble under these conditions. The in-

terchange can take place only when new molecules in the joint wall will be freer from stress than the molecules originally there, and will be entirely stable in their rôle as substitutes. This condition will be satisfied by that molecule among those present in solution, which will remain stable while sustaining the greatest amount of stress. Let it be supposed that this molecule is calcite. In whatever places the stress is less than the limit of the capacity of calcite to withstand smaltite and niccolite being more stable than calcite under conditions of less stress, replace it, or are precipitated in its stead, and likewise for silver.

(*d*) The manner in which the veins at Cobalt have grown is well illustrated in several of Mr. Whitehead's photographs; and a study of them can not help but throw light upon the foregoing discussion. Plate VIII., *b*, shows how a joint upon which mineralization has occurred has been the plane of inception for a type of preliminary mineralization, which has introduced macroscopic plagioclase crystals into conglomerate walls in advance of the more intense vein-replacement, making a broad band of lighter colored rock along the joint. Immediately following it, the second stage of mineralization has replaced this feldspathic zone by calcite. This in turn has begun to undergo replacement by smaltite, immediately following it on the axis of the joint. This photograph serves the purpose well of illustrating the succession of replacements, although in actuality the process could have gone no farther than is shown, because the joint referred to is striking normal to the direction of the chief compressive stresses of the locality; and its walls are under too great compression to permit the action to go beyond the immediate vicinity of the other joint at right angles to it, which, as can be fairly well seen, is substantially mineralized, and as it happens, is being actively mined.

Plate VII., *a*, shows filled and unfilled joints parallel to a vein; and Plate VIII., *a*, shows on another vein the manner in which these are filled to make a group of reticulate veins. Both examples illustrate the typical vein structure at Cobalt, and are especially useful in showing how branching veinlets by expanding and unit-

ing may enclose angular fragments of the walls, which gradually dwindle by replacement. This, by the way, is due to the fact that the veins grow along their walls, and that diffusion permits the delivery and removal of material to and from the vein inclusions. Plate VII., *c*, shows a small vein crossing the specimen and containing calcite and smaltite, the latter replacing the former in the typical manner.

An attempt has been made in the foregoing paragraphs not to prove, but to show evidence, that the process of diffusion has a right to stand among the other recognized genetic processes, as one worthy of equal consideration.

THE BAROMETRIC METHOD OF GEOLOGIC SURVEYING FOR PETROLEUM MAPPING.

FREDERIC H. LAHEE.

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THE BAROMETRIC METHOD.

The following paper outlines the barometric method[1] as it has been applied by the writer in geologic mapping for petroleum. The method is used to greatest advantage in regions where stratified rocks have low dips and where the structure is best represented by contours, or *isobaths*. Where beds are more steeply inclined, strikes and dips are commonly obtained by compass and

[1] The barometric method, as originally devised, was first described by M. R. Campbell, who applied it in investigations for coal. See *Trans. Am. Inst. Mg. Engrs.*, Vol. 26, pp. 298–315 (1896).

clinometer and are plotted, together with the distribution of the formations, to make the ordinary geologic map.

In all geologic mapping, as is well known, rock formations or rock structures are plotted in reference to selected points, or "stations," which must be located in their proper relations to one another as regards direction, horizontal distance, and vertical distance, or difference of elevation. In the term, "barometric method," stress is laid on the fact that relative elevations are determined by means of an aneroid barometer instead of by vertical angles or levelling. The other two quantities of direction and horizontal distance, which together may conveniently be called the horizontal control, may be obtained by pacing, odometer when an automobile is employed, or any good method that is sufficiently accurate for the particular work in hand. On the assumption that the reader understands these methods of preparing the horizontal control, we shall not attempt to explain them in this paper.

THE ANEROID BAROMETER.

There is no need here to describe the mechanism of the aneroid barometer. Suffice it to say that the instrument is delicate and that it should always be handled with care. It should be carried where it is not severely jolted. It should be read while it is resting horizontally on a support or in the palm of the hand, but it should not be grasped. It should be set so that "31 inches" on one scale is directly opposite "0 feet" on the other scale, and should not be turned from this position for different localities.

Aneroids are made with various ranges of altitude. Those registering to 5,000 or 6,000 feet are most serviceable in regions where elevations above sea level are not over 4,000 or 4,500 feet. For greater altitudes an instrument made with proportionally higher registry should be employed. Under no circumstances should a barometer be used near the limits of its range.

For satisfactory results the barometer must be reliable. Few aneroids are good enough for geologic surveying. Consequently, before an instrument is selected to keep, it should be carefully tested. This may be done in several ways, as follows:

1. Gently tap the glass face with the fingers. The needle should jar slightly, not too freely, and should return to the same point at which it stood before being disturbed. If it stops now at one place and now at another, after successive tappings, while it is held always in the same position, it is unreliable.

2. Read the instrument, carry it to an upper floor in a building, or thirty or forty feet up a hill; read it; return to the starting point and read again. Two or three minutes after arriving here the needle should record the same elevation as at first, provided the ascent and descent were made within 5 or 6 minutes. Go up to the upper station once more, wait a minute or two, and read. Any considerable differences in the elevations recorded at the same station, especially if these differences are unrelated, usually indicate a poor barometer. The pause after reaching the station is to allow for a possible lag.

3. Take out the new barometer on a day's traverse and compare its readings with those of another barometer known to be reliable. In doing this observe that both barometers may not show the same elevations, estimated from zero, nor equal amounts of rise and fall, but both should rise together and fall together, and *after the readings have been corrected* (see pp. 155 to 166), the elevations obtained by both instruments should be approximately the same for the same station.

ADDITIONAL EQUIPMENT.

In addition to the barometer, the geologist will need a compass, a watch, a coördinate-ruled notebook, and a base map upon which to mark the positions and elevations of stations along his traverse. The compass should be corrected for the local declination. When two men work together in the same area, their watches should be set together. The notebook is most serviceable when ruled to fifths or tenths of inches. Any fairly accurate county, state, or property plat will generally serve for a base map. There is no need to have one that shows topographic features, although it is well to have streams indicated. If the geologist can not procure a satisfactory map of some sort, he should make or have made a

simple outline map showing a few prominent landmarks in their correct positions, so that he can "tie" his traverses on to these. Where the land is sectionized he can often sketch his own base map along with his geological work.

SYSTEM OF RECORDING STATIONS.

The writer has found it most convenient, for note-taking, to designate days by letters and stations by numbers. Thus, in a given area, the first day will be "A," the second "B," and so on until the investigation is finished. The next area will be commenced "A" again. If more than 26 days are spent in one district, the 27th day will be "AA" or "2A," the 28th "BB" or "2B," and so on. The stations on the first day will be "A1," "A2," "A3," etc.; on the second day, "B1," "B2," etc. These symbols are plotted on the base map and are recorded in the notebook, as will be explained presently.

GRAPHIC METHOD OF NOTE-TAKING.

According to the method devised by Campbell, the notes may be recorded in the form of a profile section. Fig. 20 illustrates one. To explain this, let us assume that the geologist is at Station A1. He has a sufficiently clear idea of the area to know that Sta. A1, his starting point, is rather low and that most of the stations he will visit will be above the level of Sta. A1. The barometric elevation at this station he finds is 2,460 ft. Consequently, holding the notebook with its length right and left, he chooses a horizontal line rather low on the page, in order to leave room above for higher points, and he labels its left end "2,400." Letting 1 inch equal 100 feet, the other horizontal lines are labelled accordingly, upward and downward from the first line. (See Fig. 20.)

Suppose that he arrives at Sta. A1 at 8 A.M. On the intersection of the 2,460 line and a vertical line at the left of the page, he marks a small cross or a dot to represent A1. Let the direction from A1 to the next station be due north. Along this same vertical line he writes, "A1, 8.00 A.M., No.," and any other nec-

essary information. If, as we may suppose, A. is on the top of a bed of limestone, this is plotted by the usual symbol. (See Fig. 20.)

He now proceeds 110 double paces to Sta. A2, a point here assumed to be on a ten-foot bed of sandstone, at an elevation which he reads as 2,500 ft. He arrives at A2 at 8.10 A.M. Letting the horizontal scale of the section be 1 inch equals 100 double paces (equals approximately 1/10 mile), he plots A2 according to the adopted scales. As before, he writes on the vertical line through

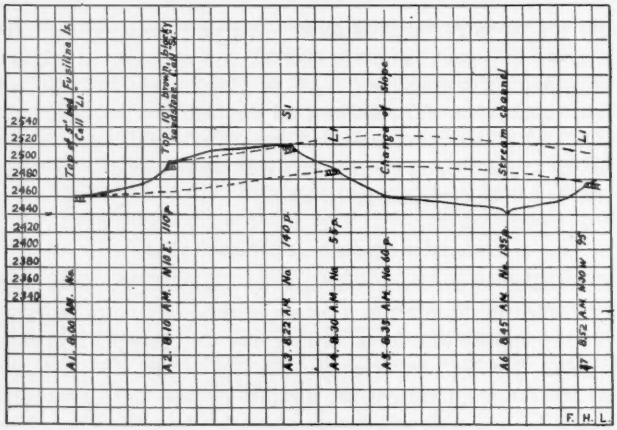

FIG. 20. Geologic profile section of a portion of a traverse. The diagram represents a page in the notebook.

the point for A2, "A2, 8.10 A.M., N10E.," the direction being from A2 to A3. To save time that might be lost later in measuring distances in the notebook, he records the number of paces from A1 to A2. He represents the sandstone bed by the convention for that rock.

In this manner he continues from station to station, recording whatever information seems to be of importance and sketching to topographic profile along his traverse. (See Fig. 20.)

Every effort should be made to settle the correlation of the

strata during the course of the field work, and the correlations should be suggested in the section by dashed lines, as in Fig. 20. The profile section is carried from page to page, care being taken to keep the elevation coördinates as nearly as possible in the same relative positions on the sheet.

TABULATION METHOD OF NOTE-TAKING.

In many cases much time may be saved by keeping the notes in tabulated form. This may be done especially when speed is required, when travel is done by automobile, and when a structure contour map, and not a geologic section, is the principal graphic result to be attained. The following plan of tabulation has been found to be serviceable. The facts indicated in Fig. 20 are recorded in this table.

TABLE I.

Station.	Time.	Barometer.	Corrected Barometer.	Direction From Last Station.	Distance From Last Station.	Remarks.
	A.M.				Paces	
A1 ...	8.00	2460		No.		Top of 5′ bed yellowish ls. Abundant Fusilina. Call L1.
A2 ...	8.10	2500		N10E	110	Top 10′ brown blocky ss. Call S1.
A3 ...	8.22	2520		No.	140	S1.
A4 ...	8.30	2490		"	55	L1.
A5 ...	8.35	2460		"	60	Change of slope.
A6 ...	8.45	2440		"	135	Stream channel. No outcrops.
A7 ...	8.52	2475		N30W	95	L1.

If an automobile is used, the trip distance is recorded in the sixth column. The fourth column is left blank to be filled in subsequently with the corrected barometric readings (see below). As in the graphic method of taking notes, the positions of the stations are to be marked on the base map.

NECESSITY FOR THE CORRECTION OF BAROMETRIC READINGS.

If a barometer is left in one place for twenty-four hours, the needle will alter its position on account of variations in atmos-

pheric pressure. Ordinarily it is swinging slowly down[2] from dawn until 9 or 10 o'clock; then it remains nearly steady for an hour or two; then rises, at first slowly and later, by 1 or 2 P.M., more rapidly until between 4 and 6 P.M., when it again changes and begins to fall. This it continues to do, although at a slackened rate, until after dawn. These movements are illustrated in Fig. 21.

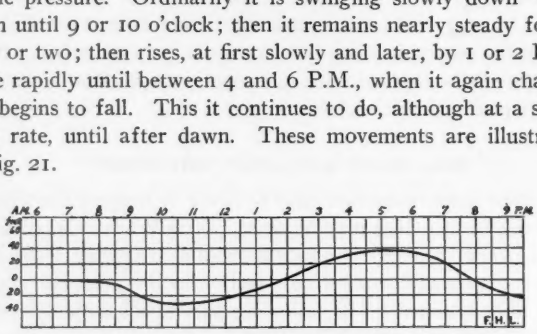

FIG. 21. Type curve illustrating diurnal variations in atmospheric pressure from 6.45 A.M. until 9.30 P.M. on a day when conditions were exceptionally steady. Compare Fig. 23.

There is some variation, both from day to day and from season to season, in the time of the changes from rise to fall, and from fall to rise. These commonly occur a little while after sunset and two hours or so after sunrise.

This regular curve of diurnal barometric variation is more or less modified by local fluctuations in atmospheric pressure such

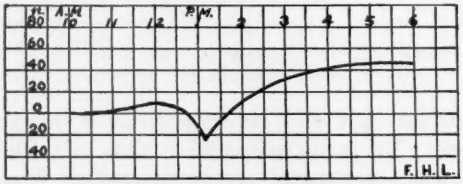

FIG. 22. Curve of atmospheric pressure variation during a thunderstorm, plotted from observations made at frequent intervals at a single station.

as may be caused by gusty winds, "twisters" or "baby tornadoes," irregular air currents due to the effects of strong topo-

[2] *Down* and *up* are here used in reference to the scale in feet, for elevations. When the needle points to successively lower elevations, it naturally indicates higher pressures in inches of mercury.

graphic relief, and especially by storms. (See Figs. 22 and 23.)

Since variations in atmospheric pressure are constantly in progress, the elevations indicated by an aneroid while traversing are incorrect. All through the day atmospheric changes are being superposed, as it were, upon relief variations, and before the recorded barometric readings can be regarded as truly representing differences in topographic relief, the atmospheric variations must be eliminated. To a certain extent this may be done by reference

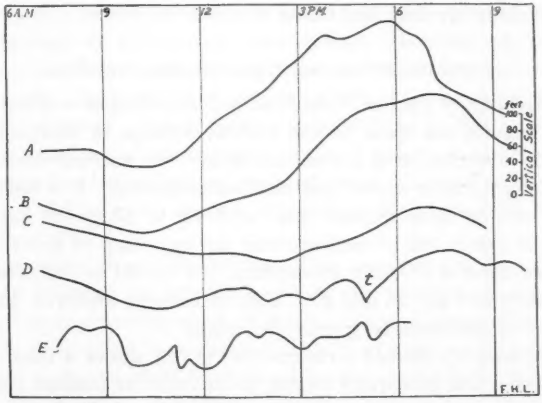

FIG. 23. Examples of atmospheric pressure curves, as indicated by barometric readings, on different days. *A* to *D* are by same barometer. *E* was plotted from the record of a poor barometer. *A* and *B* show abnormally large increases of pressure during the afternoon. *C* is abnormally flat. *D* is characterized by several rises and falls due to unsteady weather conditions. A thunderstorm occurred during the drop at *t*. The great diversity of these curves shows how great may be the errors due to correcting barometric readings by the use of a type or average curve.

to a type atmospheric pressure curve, like that in Fig. 21, which the geologist can obtain by a barograph (see p. 159), or by observations on his or another aneroid when it is not in use in the field, or otherwise; but correction by this means is very rough and large discrepancies may result from the effects of the local

atmospheric variations. (See Fig. 23.) The method should be avoided when possible and should never be employed unless the allowable error in elevations is large.

The only safe way to eliminate the effects of atmospheric pressure is by *checking the barometric readings* at frequent intervals during the field work. It is safe to say that the proficiency of the geologist in the barometric method of mapping and the accuracy of his results depend almost wholly upon his skill in checking and correcting the barometric readings. The more important methods of checking are described below.

METHODS OF CHECKING BAROMETRIC READINGS.

Checking by Two or More Readings at a Station.—When several minutes are spent at one station, perhaps in studying the fossils or rocks, or in automobile delays, the aneroid should be read shortly after arrival and just before leaving. It is better to wait two or three minutes after arriving to allow for lag. A distinct rise or fall in the barometer during a stop of thirty minutes or more is probably atmospheric and should be recorded, as at Sta. 7 in Figs. 26 and 27. Usually changes observed during shorter stops hsould be given little weight.

Checking by Branch Traverses.—Fig. 24 shows a map of a traverse. The geologist's course, in the order of stations visited,

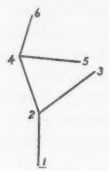

FIG. 24.

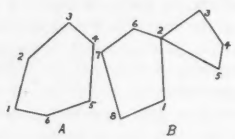

FIG. 25.

FIG. 24. Plot of course to illustrate checking by branch transverses.
FIG. 25. Plots to illustrate checking by closed and intersecting transverse.

was 1, 2, 3, 2, 4, 5, 4, 6. At 2 and 4, each, he obtained two readings which served to indicate whether the atmospheric pressure curve was steady, rising, or falling while he visited 3 and 5, re-

spectively. For example, if his instrument showed an elevation of 1,140 ft. at Sta. 2 when he first arrived there and an elevation of 1,150 ft. at Sta. 2 after his return from Sta. 3, the atmospheric pressure increased 10 feet while he made the branch traverse to 3. By this method, the effects of lag are largely eliminated by reading always upon arrival at the station; but it has the disadvantage that serious discrepancies may appear at the end stations of adjoining branch traverses, as at 3 and 5. When such branches are near, the geologist should connect them, going, for instance, from 5 to 3, before he returns to 4.

Checking by Closed and Intersecting Traverses.—A closed traverse is illustrated in Fig. 25*A* and an intersecting traverse in Fig. 25*B*. The progress of the geologist is in the sequence of the station numbers. When he returns to 1 from 6, Fig. 25*A*, his aneroid reading will show what the total change in atmospheric pressure has been since he departed from 1 toward 2. In the method of Fig. 25*B* a check is obtained on the atmospheric curve at 2 and at 1.

The reader should observe that there is nothing in these methods of checking to indicate just how the atmospheric pressure varied in the intervals between checks. Thus, it might have risen 10 ft., or it might have dropped 10 ft. and risen 20 ft., and the result, as far as could be detected by the checking, would have been the same in either case. The error would be in the elevations at the intermediate stations. The closed and intersecting traverses have the advantage of distributing such errors among all the stations in the closure, so that the error at any one station is relatively small. Obviously the shorter the time allowed to elapse before checking, the less opportunity will there be for large errors.

Checking by Return Traverse.—If the geologist returns on the same day along the same route, he may read his barometer a second time at several, not necessarily all, of the stations of his traverse. The double record at each of these check stations will indicate the amount of atmospheric pressure change between the visits to this particular station. This is like a combination of the first and second methods of checking. It is useful especially

in automobile work in rough country where roads are few and are more or less parallel, perhaps following steep-sided divides or narrow canyons. It will suffice for a single day's work, or it may be repeated on successive days, but before mapping in such a region is complete, these parallel or radiating traverses must somewhere be connected and tied in on one another by occasional cross-country traverses, even if these have to be made on foot.

Checking by Comparison with a Barographic Record.—A barograph is a contrivance which runs by clockwork and automatically registers changes in atmospheric pressure. It is left stationary as near as possible to the area being studied by the geologist. Because, under any circumstances, the field work must be at some distance from the barograph, local atmospheric variations may affect this instrument and not the aneroid which the geologist carries; or vice versa. Hence the barograph, although a useful help, is not sufficient in itself as a means of checking. Furthermore, the scale of the barographic record is too fine for reading small variations. The instrument is an added care and inconvenience, and is actually unnecessary for satisfactory correcting.

Checking by Hand Level.—Both sight and telescopic hand levels may be used to considerable advantage in checking barometric readings at stations of approximately the same altitude. The geologist may level from one point to another visible point from which he has come or to which he is going, and if the two stations differ in elevation, he may estimate this difference. Assuming, for example, that the hand level shows Sta. 1 to be 10 ft. higher than Sta. 2, and the barometer indicates that Sta. 1 is 20 ft. higher than Sta. 2, then the atmospheric pressure has risen 10 feet in the time elapsed while going from Sta. 1 to Sta. 2. Whenever a check is made by hand level, the fact should be recorded in the notebook. Care should be taken to see that the hand level is in perfect adjustment.

Checking by Eye.—The seventh method of discovering the variations of atmospheric pressure is more general in its nature than the other six. It is simply the constant comparison, by eye,

of the true slopes and elevations of the ground traversed with the observed barometric readings. It is fairly difficult for it requires experience and judgment. It means that the geologist must have an idea not only of the topography, but also of the structure, which he is crossing, and it means that he must give constant attention to the barometric elevations which he records. This method is particularly valuable for catching sudden rises and falls of the barometer entirely inconsistent with the true relative elevations. Such sharp changes do occur, especially in the vicinity of thunderstorms, and they should be detected if possible, for otherwise a rise or a fall that actually happened within a few minutes and while the geologist moved only a short distance, may be distributed over a much longer period of time and a larger part of the traverse, thus leading to an erroneous profile of the ground and most probably a distorted geologic structure.

Checking on an Established Control.—If there are points, such as U. S. Geological Survey bench marks, Geodetic Survey monuments, and railroad stations, of which the true elevations have already been established in the region to be geologically surveyed, these points may serve as a control for correcting the barometric readings. The traverses should be planned so as to include such stations. To illustrate the method, let us suppose that Fig. 26 is

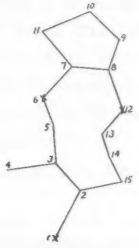

FIG. 26. Plot of a traverse. The correction curve for the barometric elevations on this traverse is shown in Fig. 27.

the plot of a traverse. The crosses are stations of which the true elevations have been determined. If the true elevations of 1 and 6 are 700 ft. and 630 ft. above sea level, respectively, and the

barometric elevations at these same stations were recorded as 775 ft. and 750 ft., respectively, the barometer was reading 75 ft. too high at Sta. 1 and 120 ft. too high at Sta. 6; that is, while the geologist went from 1 to 6, the atmospheric pressure curve rose 120 ft.—75 ft. or 45 ft.

In the course of a barometric survey, points are often chosen to serve merely for checking the barometer. They may have no geologic interest whatever. They should be conspicuous objects, such as gates, road intersections, or section corners, which may be readily described and easily recognized, so that they may be found without trouble at a later date and by any other geologist. Such stations, if their elevations are properly corrected, are really a control for the geologic work.

Where there are plenty of good roads in the area to be investigated, and the study and mapping of the rocks is likely to require much cross-country traversing on foot, a good plan is to run the roads in an automobile and thus quickly establish a control system of stations of this kind, to which the foot traverses may subsequently be tied. This is best done in the morning when the barometer is most steady. On the other hand, if exposures are sufficiently numerous along the roads in such a country, there is no need to prepare a control system *in advance of* the geologic work.

We may add that any station of a previous day's traverse, if its elevation has been corrected and fixed, may be used as an established control point for later traverses. Indeed, the geologist should never fail to tie the traverse of each day to several stations of the traverses already made on foregoing days in the region, for it is only in this way that the elevations of scattered points throughout an extensive area can be determined in their proper interrelations.

PLOTTING THE CORRECTION CURVE.

The following is a brief explanation of the plotting of the atmospheric pressure curve, or, as we have called it here, the *correction curve*.[3] Let Fig. 26 represent a traverse in which several

[3] This curve, as it is derived from observations on the aneroid barometer, is to a large extent indicative of actual variations in the pressure of the

methods of checking have been employed, yielding the results listed in Table II.

TABLE II.

A. Station.	*B.* Time.	*C.* Barometer.	*D.* Corrected Barometric Readings.	*E.* Elevations Previously Established.
	A. M.			
1	6.00	625	700	700
1	7.30	620	700	700
2	8.00	575	660	
3	8.20	580	665	
4	8.50	685	780	
3	9.15	565	665	
5	9.30	535	640	
6	9.40	525	630	630
7	10.00	540	650	
8	10.25	505	615	
9	10.45	520	630	
10	11.10	550	660	
11	11.45	595	700	
	P. M.			
7	12.15	550	650	
7	1.00	560	650	
8	1.15	535	615	
12	2.00	560	635	635
13	2.20	570	640	
14	2.35	590	655	
15	3.00	620	680	
2	3.30	605	660	
1	3.50	650	700	700
1	5.30	655	700	700
1	7.05	640	700	700

Camp is at Sta. 1 which happens to have its elevation already established as 700 ft. above sea level. At 6.00 A.M. the barometric reading was 625 ft, or 75 ft. too low. For plotting the curve, take a piece of coördinate-ruled paper and, holding it with its length right and left, label every other vertical line for the hours, beginning at 6 A.M. (See Fig. 27.) Every space, right and left, will correspond to thirty minutes, and smaller intervals of time can be interpolated. Label a horizontal line near the middle of the page "0"; label the next line, both above and below the 0 coördinate, "20," the next "40," and so on, as far as seems necessary. The horizontal coördinates below the coördinate rep-

atmosphere; but it no doubt includes, also, certain indeterminable irregular fluctuations consequent upon the individual peculiarities of the barometer. These fluctuations, as well as the atmospheric pressure variations, are for the most part eliminated by the application of the correction curve.

resent quantities, in feet, to be added to the barometric elevations to obtain corrected elevations, and those above the 0 line represent quantities to be subtracted from the barometric readings to obtain corrected elevations. Since the first reading, at 6.00 A.M., was 75 ft. too low, 75 ft. must be added for correction. March a cross (for an established station) at a point on the 6.00 A.M. vertical line ¼ of a space up from the 80 ft. horizontal line. At 7.30 A.M. the barometer read 80 ft. too low. Mark the intersection of the 7.30 vertical line and the 80 ft. horizontal line. Between the two visits to Sta. 3, at 8.20 and 9.15 A.M., the barometer fell 15 ft.. Somewhere well below the probable position of the curve to be drawn through the points just plotted marked a point (*m*, Fig. 27) on a horizontal line at 8.20, and

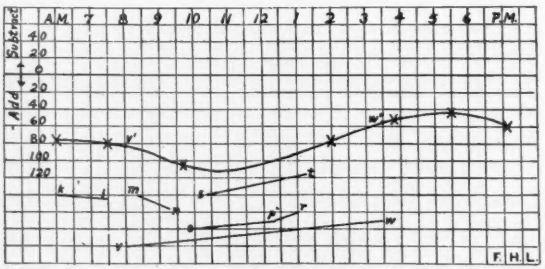

FIG. 27. Correction curve (curve of atmospheric pressure variation) for barometric elevations recorded on the traverse plotted in Fig. 26. The diagram illustrates the lower part of a page in the notebook.

another point (*n*, Fig. 27) ¾ space (= 15 ft.) below *m* on the 9.15 line. Draw a straight line between *m* and *n*. *mn* may be called a *guide line*. It is not necessarily parallel to the ultimate correction curve (*cf. st* and *vw*, two other guide lines), but merely indicates to the eye that points in the curve corresponding to the ends of the guide line are related to one another exactly as they are in the guide line. This will become clearer presently.

At Sta. 6, at 9.40 A.M., the barometric reading was 105 ft. too low. Mark a cross (again for an established elevation) where the 105 coördinate intersects the 9.40 coördinate.

At Sta. 7 readings were made at 10.00 A.M., and 12.15 and 1.00 P.M. 12.15 to 1.00 was the lunch period. Again, below the region of the curve, construct another guide line, *opr*, *o* being at the intersection of any horizontal line and the 10.00 A.M. vertical, *p* being 10 ft. above *o* and on the 12.15 coördinate, and *r* being 10 ft. above *p* and on the 1.00 P.M. coördinate. The ten-foot intervals correspond to the rise of the barometer from 540 to 10.00 to 550 at 12.15, and from 550 at 12.15 to 560 at 1.00 o'clock.

Similarly a guide line is plotted for Sta. 8, visited twice, and for Sta. 2, visited twice. Also crosses are plotted at 2.00 P.M. and 75 ft. for Sta. 12 (see columns *C* and *E*, Table II), and at 3.50 and 50 ft., at 5.30 and 45 ft., and at 7.05 and 60 ft., these last three being readings at Sta. 1.

The correction curve is drawn through the plotted crosses, which indicate the actual corrections to be made, and in such a way that points in this curve are the same distances apart, vertically and horizontally, as the end points of the several guide lines, vertically below. For example, *v'* is in the curve at 8.00 A.M. and *w'* is in the curve at 3.30 P.M., 30 ft. higher than *v'*, These are exactly the relations of the end points of the guide line *vw*, but, to repeat what was stated above, the curve between *v'* and *w'* is not by any means necessarily parallel to the guide line *vw*.

Observe that two or more readings may be taken at the same station before starting in the morning and after returning in the afternoon. These additional observations are seldom made by geologists, but the writer has found them to be of considerable value in showing the slope and general tendency of the curve. Note also that the curve is drawn through the crosses, that is, through the points that indicate the corrections to be applied as stations previously established. The guide lines are obtained by checking. In this traverse (Fig. 26) checking was accomplished by reference to control stations at 1, 6, and 12; by closure at 2, 7, and 8; by branch traverse at 3; and by two readings with intervening wait at 7.

APPLICATION OF THE CORRECTION CURVE.

By means of the correction curve, constructed after the manner above described, any barometric readings made during the day may be corrected. However, to save time, only those stations should be corrected which are needed for making the structure contour map. If notes were kept by the graphic profile method, the corrected elevations may be written against the proper points in the profile section. If the notes were tabulated, the corrected elevations are to be written in a column for the purpose. (See Tables I. and II.)

For illustrations of the way in which corrections are made, let us take Sta. 14 (see Table II.). The barometric elevation for 14 was observed to be 590 at 2.35 P.M. A point at 2.35 P.M. in the curve, Fig. 8, is just below the horizontal line that would represent "add 65 feet." Approximately 65 feet, then, should be added to the recorded reading, 590, thus giving the true elevation at 655 ft.

Where stratigraphic intervals must be added to or subtracted from the elevations of certain strata in order to obtain elevations on a chosen key bed, this may be done at the same time as the correction of the barometric readings, and the *true elevation of the key bed* may then be entered in the notebook, in the manner suggested above, ready to be copied on to the map.

DEGREE OF PRECISION OF THE BAROMETRIC METHOD.

The feeling is widespread among geologists that the barometric method is at best inaccurate and uncertain in its results. As far as the writer has been able to observe, this is not quite the case. If the geologist and his aneroid are reliable—and a satisfactory aneroid *can* be found by careful testing of several instruments—the accuracy of the results will be directly proportional to the frequency of the checking. The fewer the checks and the greater the interval of time permitted to elapse between checks, the smaller will be the chance for catching changes in atmospheric pressure and, hence, for obtaining true relative elevations by reference to the correction curve.

For detailed mapping, check stations should not be over a mile or two apart, and not over an hour should elapse between checks. When, on the other hand, the object is to prepare a small scale map of an extensive area and to show only the larger structures, travel is usually much more rapid, minor details are omitted, check stations are selected at 5, 10, 15, or even 20 miles apart, depending on the rate of progress possible, and the barometric elevations are checked at intervals of from one to three hours.

The reader will perceive that the barometric method is highly elastic. It can be made slow and fairly precise, or rapid and less accurate. In other words, it may be adapted to both detailed and reconnaissance geologic mapping. Under ordinary circumstances, whether progress is slow or rapid, the average relative error may be made less than 1 vertical in 1,000 horizontal, which is usually less than the variations in thickness of the strata.

To illustrate how closely corrected barometric elevations may check, we may cite an example. Three traverses were run, one from *A* to *B*, another from *B* to *A*, and a third from *B* to *C*. The elevations of *A* and *C* were known. That of *B*, 80 miles from *A* and 90 miles from *C*, was to be determined. A day was required for each traverse. Correction of elevations along the routes followed was made independently for each traverse. The corrected elevation of *B* was found to be 2,365 ft. in the first traverse, 2,360 ft. in the second, and 2,365 ft. in the third. 2,365 ft. was accepted as the elevation of *B*.

RATE OF MAPPING.

Detailed mapping, involving sufficiently careful field work to enable the geologist to prepare a reasonably accurate contour map of the geologic structure on the scale of ½ to 2 miles to the inch with a contour interval of 10 to 20 feet, may be done by the barometric method at rates varying from 2 to 50 square miles per day. 2 to 4 square miles should be mapped in a day where foot traversing is necessary. From 10 to 50 square miles may be mapped by automobile. More than 25 square miles as a day's work is exceptional.

In more rapid reconnaissance, for a map, let us say, on a scale of 2 to 10 miles to an inch and with a contour interval of 25 to 100 feet, as much as 100 square miles, or even more, can sometimes be surveyed by automobile in a day.

For both detail and reconnaissance work the size of the area examined in a day depends upon the number, condition, and distribution of roads, the abundance of outcrops and ease of correlation of strata, and whether or not the geologist has a helper to drive the car.

COMPARISON OF THE BAROMETRIC AND PLANE TABLE METHODS.

There can be no question that the plane table method of geologic mapping, when performed by competent men, is more precise than the barometric method. On the other hand, the latter has several advantages which make its practice more desirable under certain conditions. In closing the present paper, we may well compare some of the advantages and disadvantages of the two methods.

Among the advantages of the barometric method are the following:

1. It requires only one man, whereas the plane table method requires at least two, namely, an instrument man and one or two rodmen.

2. It is very elastic in its possibilities of speed and degree of precision attainable, and these factors are to a considerable extent within the geologist's control. The plane table method is more limited in this respect.

3. The equipment for the barometric method is much lighter and more easily portable than that for the plane table method.

4. The barometric method is more satisfactory than the plane table method in forested areas and regions of low relief, where the intervisibility of points is poor.

Some of the disadvantages of the barometric method are:

1. Satisfactory barometers are difficult to secure.

2. In general this method requires a more experienced, and therefore a more highly salaried, man than does the plane table method.

3. Since, in the barometric method, it is customary to follow north-south and east-west lines, or roads, or property boundaries, or other definite directions, the traverses usually cross outcropping strata, making correlation very difficult where the beds are not easily recognized. Under these circumstances the plane table method is more satisfactory since the rodman may "walk out" or trace the outcropping beds and so facilitate their correlation.

4. The barometric method necessitates the correction of the barometric readings before the map can be made, whereas, by the plane table method, the mapping may be practically completed in the field.

DALLAS, TEXAS.

A LABORATORY METHOD FOR THE EXAMINATION OF WELL CUTTINGS.[1]

EARL A. TRAGER.

Introduction.—With the growth of sub-surface study there has developed a need for a more accurate knowledge of the formations penetrated by the drill than that which is to be had from the driller's log. The many variations in a number of driller's logs from a given locality are due chiefly to the lack of ability on the part of the driller to recognize the different types of sediments. Most drillers readily recognize a shale or slate, a lime, or a sand, but if they strike a sandy-shale or a sandy-lime they find themselves without a term to describe it, and it is at these points that variations begin to appear. The many possibilities for error will readily suggest themselves and are too numerous to mention here. However, as long as no source of information other than the driller's logs these are used as a basis for plotting the prominent features in sub-surface structure, such as thick limestone members or prominent sands. These features are more or less uniform in all logs, but the information shown in the logs between these points is of little value. This is especially true of the logs from the Mid-Continent field because of the many thin beds of different types of sediments which appear between each prominent marker.

The work which has been done with this rather unsatisfactory information has demonstrated that there are vast stores of geologic knowledge to be obtained from the study of well logs, and obviously the more accurate and complete the log the more accurate will be the information obtained therefrom. Just how to proceed to obtain an accurate log of any given well has been a problem ever since drilling began. The best solution to-day is the

[1] Published by permission of chief geologist, Empire Gas & Fuel Co.

practice of sampling the cuttings and then compiling a log which is based on a study of these cuttings.

Operators in the past have objected to taking cuttings because many drillers refuse to be burdened with the added task, and to keep an extra man at the well to sample the cuttings from every screw adds considerably to the cost of the well. But, as development is progressing into areas where little can be learned from the surface geology, the need of cuttings is being increasingly felt and it is to be hoped that in the near future there will be a representative set of cuttings available for study from every well drilled.

The purpose of this paper is to suggest a method for the study of such cuttings, a method which is sufficiently rapid to be practical for the oil operator and one which will furnish reliable data which may be used for the construction of accurate sub-surface maps.

Method of Analysis.—Cuttings of a mixed nature from sedimentary deposits are very deceiving and an examination of a set of cuttings with the aid of a lens and a little acid is of little more value for the interpretation of the geologic history of an area than is the driller's log itself. There are a few students whose work on the examination of well cuttings is an exception to this statement. On the other hand, a complete chemical analysis of the cuttings from each screw is practically worthless, this being especially true when drilling through a series of beds, each of which is less than five feet in thickness. A chemical analysis by itself is difficult to interpret in terms of sedimentation. As an example, if an analysis of a single cutting shows it to contain: 5 per cent. lime, 30 per cent. sand, 65 per cent. shale, the following are several of the interpretations which might be made, using this information as a guide:

Case I.	Case II.	Case III.
65 % shale	70 % limy-shale	95 % sandy-shale
30 % sand	30 % sand	5 % lime
5 % lime		

Other combinations will suggest themselves, and each combination will call for a modification in the theoretical conditions of

deposition. A physical examination without some form of an analysis falls short in that it does not tell the amount of each member, *i.e.*, sand, shale, and lime, present in a mixed sediment. Because of these factors a method was developed which is a combination of a physical examination and a chemical analysis that has proved very satisfactory. The method here described is little more than an outline and no doubt numerous variations from this scheme will be developed by individual workers.

Physical Examination.—For convenience all work is done in units of twenty-five samples.

The first work to be done on a sample is the physical examination. The sample is poured upon a sheet of white paper, examined and described under the following heads:

I. Color.
II. Size of grains or fragments.
  FFF, powdery,
  FF, very fine,
  F, fine,
  MF, medium-fine,
  M, medium,
  MC, medium-coarse,
  C, coarse.
III. Type of grains or fragments.
  C, gumbo,
  Xyln, crystalline,
  A, angular,
  Sa, sub-angular,
  R, rounded,
  S, saccharoidal,
  V, vitreous,
  F, frosted.
IV. Fossils, or characteristic minerals present, *e.g.*, pyrite, coal, selenite, etc.
V. Remarks.

Under the heading "Remarks" is placed all information which

will aid in interpreting the chemical analysis in terms of deposition. The most abundant material is listed first and the remainder in the order of its importance. Mixed sediments are described as such under this heading, the following examples will illustrate this point:

Soft, white limestone, with some green shale.
Sandy-shale and a small amount of limestone.
Free sand grains and a small amount of shale.
Gray limestone, and sandy shale. Many Fusulina.
Soft, red shale with a few selinite crystals.
Soft, limy-shale.
Hard, dense shale; gray limestone.

Just a brief description such as that indicated in each line above is sufficient to prevent any gross error in the interpretation of the analysis.

Chemical Analysis.—After this description is recorded the sample is ready for the chemical analysis. A 10 c.c. sample of each cutting, after it has been described, is placed in a small vial before the sample is returned to the bottle in which it is kept, and when a set of 25 vials are filled they are sent to the laboratory.

The following is an outline of the method for the analysis:

Grind the sample to a powder taking care not to grind it too fine or it will be difficult to distinguish the sand from the shale. Sift the powder through a 70 to 80 mesh sieve. Mix well the portion that passes through the sieve and measure a 5 c.c. sample by pouring the powder through a small funnel into a 10 c.c. tall-form graduated cylinder. Do not pack the powder by jarring, the only shaking permissible is just enough to destroy any openings that may develop.

Place the 5 c.c. sample in a 100 c.c. porcelain evaporating dish and cover it with 50 c.c. of 50 per cent. hydrochloric acid. Place the dish on a hot plate and evaporate the acid nearly to dryness. Care must be taken not to evaporate it too far or part of the material will be lost by spattering.

Now remove the dish from the hot plate, cool, and add about 10 c.c. of water to the residue. This step removes the lime by putting it into solution.

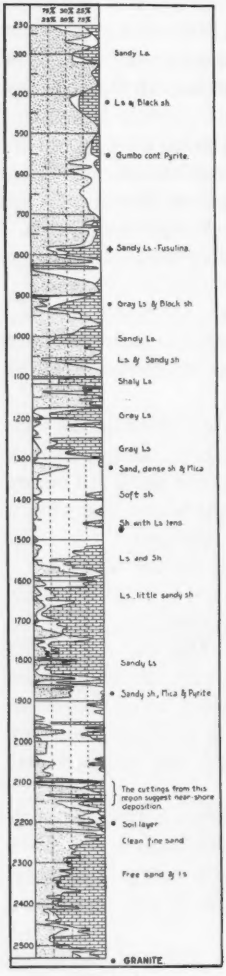

FIG. 28.

Transfer the residue to a 50 c.c. graduated centrifuge tube and make up to about 25 c.c. with water. Shake the tube well and place it into a rack and allow the residue to settle for about 10 minutes, then place the tube in a centrifuge and rotate it for five minutes at a speed of about 700 R.P.M. If the liquid over the residue is clear at the end of this time, pour most of it off and return the tube to the centrifuge and whirl it until the residue has reached a constant volume.

This treatment separates the sand and shale, the dividing line generally is quite sharply defined, excepting in cases where the sample was ground too fine. The per cent. of sand and shale is read directly and the per cent. of lime is obtained by difference.

This analysis will give very satisfactory results except in a few cases where the sample contains a type of shale that forms a gelatinous precipitate as a result of this treatment. This precipitate can easily be recognized by its appearance and by its great increase in volume. In such cases the sand can be determined in the usual manner and a determination for lime can be made on a separate sample. The shale can then be computed by difference.

To check this method of analysis a number of duplicates were analyzed by several detailed, quantitative methods. This work demonstrated that there is a constant error of from 5 to 30 per cent. in the shale and lime determinations when run under aver-

age laboratory conditions by this method, due to the fact that the samples are not left in the centrifuge until all the water is removed from the shale. With a reasonable amount of care in centrifuging the error may easily be kept within 10 per cent.

Recording of Information.—The method of recording the information derived from a study of well cuttings, such as that just outlined, is of as great importance as the information itself; because, if this record is kept in too bulky a form it is a laborious task to correlate or compare a number of such records. In our laboratory we keep two sets of records; one in the form of a permanent record which is kept in a bound book; the other is a graphic log which is placed on a narrow card for convenience in handling.

The graphic log is the one most often consulted. This log contains a colored graph showing the per cent. of sand, shale, and lime present every five feet, and beside this graph is placed a brief description of any important characteristics which may occur at various intervals.

The accompanying diagramatic log illustrates the scheme of the graphic logs. The distance across the log represents 100 per cent. and the per cent. of sand, shale, or lime present at any given horizon can easily be ascertained by noting the area covered by the color which represents each type of sediment, *e.g.*, the reading at 270 feet is 50 per cent. sand and 50 per cent. shale, at 300 feet is 60 per cent. sand and 40 per cent. lime, and at 570 feet is 55 per cent. sand, 35 per cent. shale, and 10 per cent. lime. To make this relation stand out more vividly we color the area representing sand, red; shale, green; and lime, blue, in the logs which are constructed for daily use.

The permanent record contains all the information that has been collected relative to any given set of well cuttings. When correlation passes beyond the general stage, such as can be made by the use of the graphic log, this record is consulted for more specific information.

The following is the outline for this record which is used in our laboratory, and several descriptions taken at random from

the log which accompanies this paper are given to illustrate the method of recording this information:

NAME OF WELL, John Doe.
Sec. 10. Twp. 25S. Range 5E.
COUNTY Butler. STATE Kansas.

Depth.	Color.	Size of Frag.	Type of Fragments.	% Sand.	% Shale.	% Lime.	Symbols.	Remarks.
736	DG		Gumbo	20.0	80.0	0.0		
1310–1320	Bk	F	Sa	10.0	50.0	40.0		Black sh., dk. ls.
1673–1679	DG	M	R–Sa	50.0	50.0	0.0	o	Dense sh., much mica.
1771–1779	G	M	A	4.0	6.0	90.0	+	Ls. cont. Crinoid stems.
2105–2108	W	M	A	35.0	40.0	25.0	o	Cherty ls. Amorph. Qu.
2595	R	MF	A				o	Granite.

All the headings, excepting "Symbols," are described earlier in the paper. Under this heading is placed graphic characters to attract attention to points that may be of assistance in correlating various logs. For example:

A red dot indicates a characteristic mineral or notable structure.
A black dot represents a decidedly black shale.
A red cross indicates a fossil horizon.
A red circle indicates a water horizon.
A red cross within a red circle represents an oil horizon.

This information can be kept in a permanent form and the possibility of loss is reduced to a minimum.

A number of such records is invaluable in constructing Paleogeographic maps and for other purposes of sub-surface study.

The author is indebted to Mr. Everett Carpenter and Mr. Alex. W. McCoy whose assistance and coöperation has made the work of the Geological Laboratory possible.

EMPIRE GAS AND FUEL CO.,
BARTLESVILLE, OKLA.

DISCUSSION.

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

MAGNETIC IRON ORES OF CLINTON COUNTY, NEW YORK.

Sir: The paper by William J. Miller in the November number of ECONOMIC GEOLOGY, relating to the magnetites of Lyon Mountain and vicinity, is a concise and altogether faithful account of the geology of an important Adirondack mining district. With most of the statements and conclusions there can be little disagreement, if one accepts the viewpoint of the more recent workers in this field of Precambrian geology. On a few points, however, it appears the writer has taken a position which invites critical inquiry from the reader, for the evidences submitted seem scarcely adequate to warrant the deductions which he makes, particularly with regard to the derivation of the ores.

The explanation of the magnetites that occur in the Precambrian gneissic rocks is primarily dependent of course upon the methods of origin ascribed to the latter. If the wall-rocks are igneous then it is reasonable to suppose the ores are connected with some magmatic process, since all the evidences go to show they were in place when the gneisses assumed their present position and structures. On the other hand if the wall-rocks are sedimentary—as they undoubtedly are in certain Adirondack districts—it is possible to ascribe various methods of genesis to the magnetites, the easiest of which is perhaps to regard them as

contemporaneous accumulations metamorphosed along with the country rocks. Still the influence of igneous activity may not be excluded, as everywhere these sedimentary or Grenville formations have been powerfully affected by the igneous invasions of the early Precambrian and these not unlikely have been instrumental in the deposition of their contained magnetites.

The country gneiss in the Lyon Mountain area is described by Miller and earlier by Cushing as having the mineral composition of a low-quartz granite. It contains some admixture with other rocks like amphibolite, dark pyroxene gneiss, mica and pyritic schists, but on the whole it is remarkably uniform and simple in character throughout the area of probably several hundred square miles that it covers in the northern Adirondacks. Cushing regarded it as igneous and Miller concurs in this view by calling it Lyon Mountain granite. With this interpretation no issue will be made, for the present writer has expressed a similar opinion.

The derivation of iron ores then centers about some magmatic process. In his contribution Miller emphasizes the importance of the foreign inclusions within the granite, particularly those of more basic character, as a source of the iron. The existence of an older gabbro is predicated upon the presence of certain hypersthene-bearing materials, as well as hornblende gneisses, both of which are considered to have been invaded by the granite during its progress toward the surface. In this process it is held the granite took up magnetite from the older rocks but also secured additional and perhaps more important supplies of iron oxides by reaction upon the hypersthene and hornblende which through its influence underwent a paramorphic change to diallage of lower iron content. The corollary of the matter is that the magnetite of the ore bodies has come mainly from these foreign sources and not from the granite itself, although the concentration of the iron in its present form must have been brought about by magmatic action in some way.

A sample of gabbro, representative of the inclusions, but unaffected by the granite, on analysis showed 11.54 per cent. Fe_2O_3 or 8.08 per cent. iron. A sample of diallage rock from near the

Lyon Mountain deposits returned 10.86 per cent. Fe_2O_3, or 7.60 per cent. iron, of which 8.16 per cent. Fe_2O_3 was in the pyroxene mineral. On the basis of the mineral analysis of the gabbro it is reckoned that the three minerals—hornblende, hypersthene and magnetite making up 60 per cent. of the mass of the gabbro—contain by themselves 18.4 per cent. Fe_2O_3, but here a little error has crept in as the correct amount on the assumed basis would be 19.2 per cent. By deducting the iron in the form of magnetite it is concluded that the hornblende and hypersthene of the gabbro have lost much iron in conversion to diallage.

The figures afford little basis for a quantitative statement of the problem. So far as they go they indicate that the gabbro with 11.54 per cent. Fe_2O_3 may have been transferred to a diallage rock with 10.86 per cent. Fe_2O_3, but not much else. There is no information vouchsafed about the equivalent volumes concerned in the operation, or the material additions or subtractions which, if the theory is correct, must have taken place. But even admitting that the gabbro contains several per cents. of iron more than the diallage rock, which is scarcely indicated by the analysis, is the mass of the gabbro that may have been ingested in the granite proportionate to the effects produced in the formation of the magnetite deposits? That is the crucial point.

The general character of the gneiss or granite does not give support to the view that it has has absorbed large amounts of foreign material, except very locally. In the Palmer Hill district to the east of Lyon Mountain the rock is nearly a pure feldspar-quartz-magnetite mixture, and in the writer's observation that is the prevailing character of it. Admixture with foreign material seems to have no bearing on the distribution of the ores in general, although in the Lyon Mountain district some of the deposits do align themselves more or less with the hornblende and mica schists enclosed by the granite. Palmer Hill and many other mines exemplify their association with granite notable for its small amounts of the dark minerals, except magnetite which not infrequently runs up to 10 or 15 per cent.

Dr. Miller himself does not seem to hold that the granite has

actually absorbed much of the gabbro, as he states that the typical rock is a microcline—microperthite—quartz material with only 8–10 per cent. of plagioclase in the form of albite and oligoclase. Consequently the abstraction of iron has been a sort of lixiviation process, without notable incorporation of the other ingredients. In any case it must be held that a very large body of the gabbro was involved, that the magmatic solutions penetrated it very thoroughly, that the iron so taken up was later segregated in order to form ores of 30–50 per cent. iron content in very substantial bodies. With such large masses the chilling effect upon the solutions would be considerable and tend to block the migration of the iron oxide. It seems likely that the iron must crystallize out close to the source of supply, so that the total effect would be one of dilution rather, through addition of the magmatic material.

Such theory also fails to account for the iron content of the granite in its normal phases. This is a matter that has not been dealt with, but it needs to be taken into consideration. In its mineral and chemical properties the rock belongs to the general type of soda-rich granites and syenites that have come to be known as the predominant magnetite-bearing rocks the world over. If segregation of the iron in the granite itself may not explain the formation of ore bodies like those in question, then our theories of magmatic processes appear inadequate.

The late crystallization of the magnetite particles which Dr. Miller notes in regard to the ores is not exceptional; also it is not necessarily indicative of a later introduction of magnetite after the crystallization of the silicates; rather it seems to depend upon the proportion of iron to the other ingredients. Thus in ordinary gabbro the magnetite or ilmenite normally crystallizes first but in the segregated ores it is the last to form.

The Precambrian magnetites present very intricate problems and their solution requires close study, such as Dr. Miller has given to the present occurrence. My criticism is that he has overemphasized certain features which really play a minor rôle in the ore-forming process.

D. H. NEWLAND.

ALBANY, N. Y.

REVIEWS.

The Copper Deposits of Ray and Miami, Arizona. By FREDERICK LESLIE RANSOME. U. S. Geological Survey, Prof. Paper No. 115, 192 pages, numerous maps and illustrations. 1919.

This is the third great monograph on Arizona copper deposits by Dr. Ransome. It is shorter than the Bisbee paper, somewhat larger than the Globe paper, and ranks with them as a lucid treatment of a complicated area containing important mineral deposits. It is the first adequate treatment of the genesis of the disseminated chalcocite deposits in schists.

Ray and Miami are located in central Arizona, about eighteen miles apart, in the belt of mountain ranges that borders the Arizona Plateau along its southwestern edge. To the end of 1918 they have yielded 1,098,409,607 pounds of copper, and the three principal mining companies have declared dividends amounting to $67,592,552, of which $8,548,050 was paid by the Inspiration Consolidated Copper Co. as a result of its first full year's operations, in 1916. Estimates give the ore originally present in the Miami district as 145,000,000 tons and in the Ray district as 115,000,000 tons. The tenor in copper ranges from about 1.5 to 6 per cent., and the average of the ore mined lies between 1.5 and 2 per cent.

The oldest rocks in the region are the Pinal schist, which consists mainly of metamorphosed siliceous sediments, and various granitic intrusives. All are pre-Cambrian. Resting on the eroded surface of these rocks are beds about 1,300 feet thick, supposed to be Cambrian. Above the Cambrian is 325 feet of limestone, probably Devonian. Above the Devonian is Carboniferous limestone, at least 1,000 feet thick.

After the deposition of the Carboniferous limestone, the region was uplifted and eroded. At about the same time diabase was injected into fissures in the older rocks, and from these fissures the magma was forced as sills between the beds, so that great masses of strata were driven apart and in places were completely enveloped in the igneous rock.

The intrusion of the diabase was probably followed by erosion and possibly by the deposition of Cretaceous sediments. The deposition of the supposedly Cretaceous beds was succeeded by andesitic eruptions.

The andesitic eruptions were followed by the successive intrusion of (1) quartz diorite, (2) granite, quartz monzonite porphyry, and grano-

diorite in masses, some of which, as the Schultze granite, are several miles in diameter; and (3) quartz diorite porphyry, in dikes and sills. The intrusion of the rocks of the second group was the cause of the original metallization that gave rise to the protores of Miami and Ray. The time of the intrusion of the rocks in these three groups is not known but is thought to have been early or middle Tertiary. Erosion followed, attended by deposition of the Whitetail conglomerate, which subsequently was buried under a flow of dacite. Later the Gila conglomerate was deposited.

Erosion attended by weathering and secondary enrichment altered enormous bodies of low grade protore to workable copper ore. The ore bodies are flat-lying masses of irregular and more or less indefinite horizontal outline. The shape and size of each body depend largely upon the lower limit set for the percentage of copper in material classifiable as ore. Generally, the ore is overlain by leached, nearly barren rock known as capping, although in places the overburden contains considerable chrysocolla and malachite. The capping ranges from 40 to 1,000 feet in thickness. The average thickness at Ray, on the ground of the Ray Consolidated Copper Co., is between 200 and 250 feet. The ore grades downward into pyritic material that generally contains too little copper to be workable. The maximum is about 500 feet, but the average thickness of the Ray Consolidated Copper Co.'s ore body is 120 feet.

The ore bodies in a very general way have a marginal position with reference to intrusive masses of granite, granite porphyry, and quartz monzonite porphyry, but the ore occurs both in the schist and in the intrusive granitic or monzonite porphyry. The greater part of the ore is metallized Pinal schist.

From the relation of the ore bodies to the present surface, it is concluded that the greater part of the enrichment was effected before the development of the present topography and probably before the eruption of the dacite. As enrichment progresses and chalcocite increases the process of enrichment becomes slower in action, and erosion may, in some circumstances, overtake it.

Although much of the enriched ore is now below ground-water level it probably was once above that level, and enrichment is believed to have taken place mainly in the zone of rock above any general water table. If it is true that the enrichment was mostly earlier than the eruption of the dacite, it must, of course, have preceded also the laying down of the Gila conglomerate. This conclusion admits the possibility of the discovery of ore underneath certain areas of the conglomerate, particularly between Miami and Globe.

W. H. EMMONS.

SCIENTIFIC NOTES AND NEWS[1]

FRANK L. HESS, of the U. S. Geological Survey, sailed for South America, December 6.

CHARLES BERKEY, of Columbia University, has been making an examination of the Hill Top Metals Company's holdings in the Chiricahua Mountains, near Douglas, Arizona.

D. H. NEWLAND, Assistant State Geologist of New York, has a six months' leave, and is spending it in geological and mining work in the West.

NELSON H. DARTON, geologist of the U. S. Geological Survey, will spend two months early in 1920 in the Dominican Republic investigating oil conditions there.

A. G. MADDREN, formerly with the Alaskan Division of the U. S. Geological Survey, and with the U. S. National Museum, has entered the employ of the Vulcan Oil Company. He will make a detailed study of part of the Ranger oil field, in Texas, working under the direction of Dr. Ralph Arnold.

E. B. YOUNG, assistant in the Geological Department of the Anaconda Copper, and Secretary of the Montana Local Section of the A. I. M. E., is publishing in the *Anode* a series of articles on geology which are proving valuable to the non-technical men of the Anaconda Company.

J. VIPOND DAVIES has been elected president of the United States Engineering Society, succeeding Charles F. Rand.

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.

A. J. MACKINTOSH BELL has returned to Almonte, Ontario. He has been at Harvard delivering a course of geological lectures.

P. E. HOPKINS, of the Ontario Bureau of Mines, is working on a report on the West Shining Tree district which will be published soon.

A. G. BURROWS, of the Ontario Bureau of Mines, with Mr. Hopkins, is preparing a detailed report on the geology of the Kirkland Lake area.

E. K. SOPER has returned from Trinidad to New York.

HOYT S. GALE has left the U. S. Geological Survey, to investigate oil in Bolivia.

WALLACE LEE, oil geologist, is now associated with the Frantz Corporation, Friederich Building, Denver, Colorado.

ELMER H. FINCH, geologist, has been appointed chairman of the Mineral Division, Land Classification Branch, U. S. Geological Survey. Mr. Finch, who succeeds Alfred R. Schultz, has been an active member of the Land Classification Branch for a number of years.

MILLARD K. SHALER, formerly on the staff of the U. S. Geological Survey and for years in charge of important Belgian-American mining interests in the Congo Free State with headquarters in Belgium, has been in the United States for a few months. He left for Belgium on January 20.

G. M. BUTLER, dean of engineering at the University of Arizona, Tucson, has been elected president of the American Association of Engineers. He addressed the section on the points for consideration before drafting an engineer-license bill.

FRANK H. SKEELS, mining engineer, of Wallace, Idaho, recently completed an investigation of the clay deposits of Idaho, under the direction of the State Bureau of Mines and geology, in coöperation with the U. S. Bureau of Mines.

THE GEOLOGICAL SOCIETY OF AMERICA announces the following nominations for officers for 1921: President, James F. Kemp; first vice-president, J. B. Woodworth; second vice-president, Arthur Keith; third vice-president, T. W. Stanton; secretary, Edmund Otis Hovey; treasurer, Edward B. Mathews; editor, Joseph Stanley Brown; councilors, 1921–1923, J. E. Spurr and G. D. Louderback. The next meeting of the society will be held on December 28–30, 1920 in Chicago.

THE AMERICAN INSTITUTE OF MINING AND METALLURGY held its New York annual meeting, February 16–20. An unusually large number of papers pertaining to petroleum geology and an unusually small number pertaining to ore deposits were presented. Several papers relating to the broader phases of the coal industry attracted much attention. The meeting was well attended by those interested in economic geology.